

Looking for Large CP Violation in $B_s^0 \rightarrow J/\psi \phi$ Decays



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Overview

- *CP* Violation:
 - Standard model
 - $B_s^0 \rightarrow J/\psi\phi$
- Measurement:
 - CDF Detector
 - Data Sample & Selection
 - Angular Analysis
 - Flavor Tagging
 - Likelihood
- Results
 - Untagged Analysis
 - Tagged Analysis

CP Violation in the Standard Model

Quark weak flavor eigenstates related to mass eigenstates by CKM Matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrization expanded in $\lambda \approx 0.23$, up to λ^5 , $V_{CKM} =$

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(1 - \rho - i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

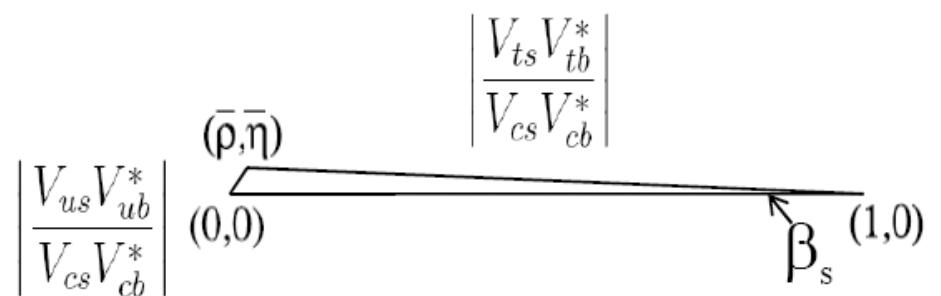
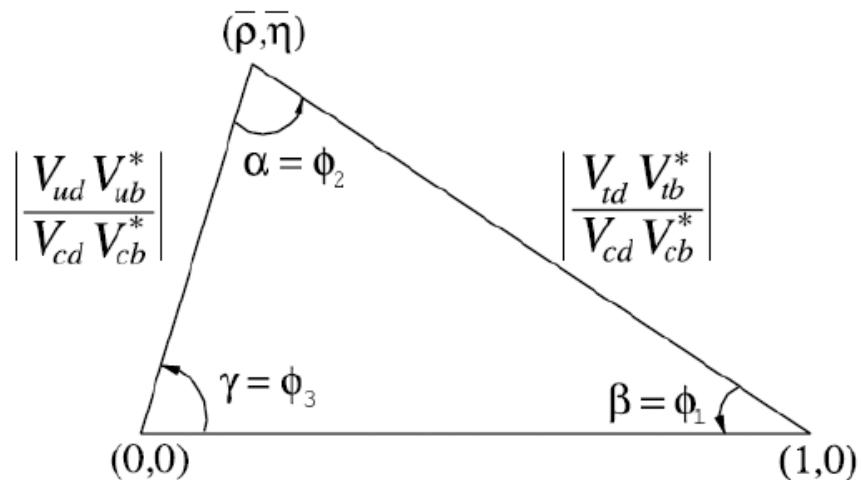
CP violation enters into elements in red. Controlled by one parameter in SM, η

Unitarity Triangles

... or how to get from one SM parameter to a very rich phenomenology.

$$B_d^0 : \quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$B_s^0 : \quad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



- Sides & interior angles can be independently measured
- Goal: to “overconstrain” the triangles
- Hope: that no single choice of CKM parameters will fit all measurements

Selective Review of CP Violation Measurements

Discovery of CP violation:

- 1964: $K_L^0 \rightarrow 2\pi$ decay, asymmetry in $K^0 - \bar{K}^0$ mixing

Since then, the standard model description has been (too) successful:

1988, '99	$K_{S/L}^0 \rightarrow 2\pi^0, \pi^+\pi^-$	Direct CPV in decay	NA31/48, KTeV
2001	$B_d^0 \rightarrow J/\psi K_S^0$	CPV in $B_d^0 - \bar{B}_d^0$ mixing	BaBar, Belle
2005, '06	$B^+ \rightarrow K^+ \rho^0$	Direct CPV in decay	BaBar, Belle
2004, '05, '07	$B_d^0 \rightarrow K^+ \pi^-$	Direct CPV in decay	BaBar, Belle, CDF
2007	$B^+ \rightarrow J/\psi K^+$	Direct CPV in decay	DZERO

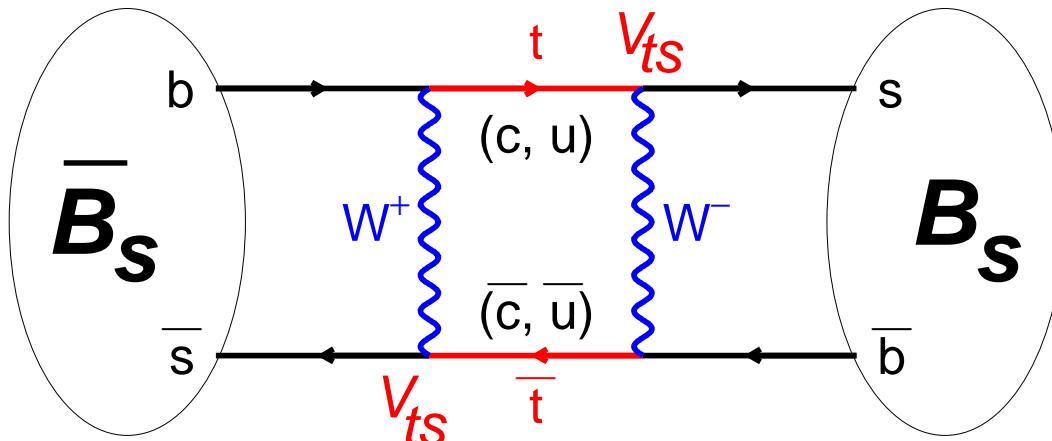
- Success of CKM both from precise determination & agreement, or calculational limitations

“Last hope” for new physics in beauty system: B_s^0 decays

- CP violation predicted to be very small in Standard Model
- If measured to be otherwise: unambiguous signal for new physics

The Neutral B_s^0 System

“Mixing” of B_s^0 meson refers to $B_s^0 - \overline{B}_s^0$ oscillation, e.g.:



Schröedinger Eq: 2 Masses, Lifetimes

$$i \frac{\partial}{\partial t} \begin{bmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{bmatrix} = \left(M - \frac{i}{2} \Gamma \right) \times \begin{bmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{bmatrix}$$

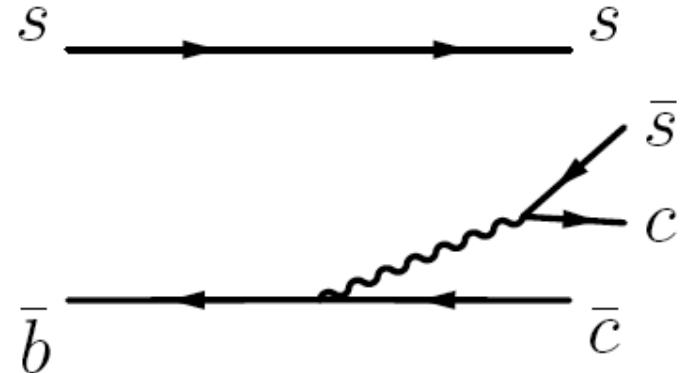
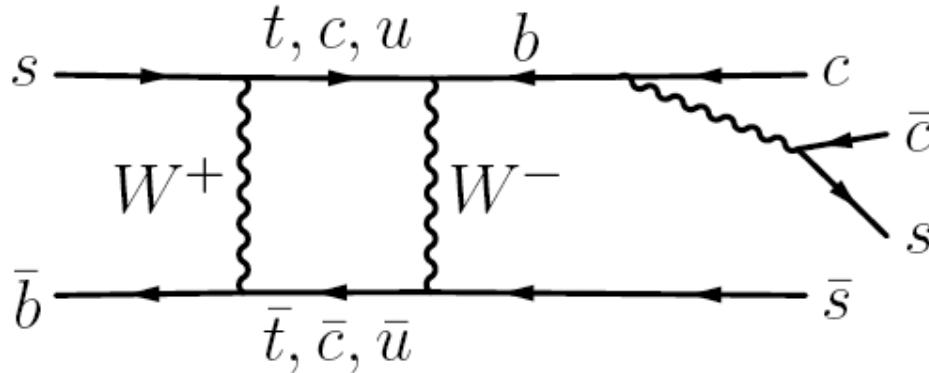
$$\Delta m_s \approx 2 |M_{12}|$$

$$\Delta \Gamma_s \approx 2 |\Gamma_{12}| \cos(\phi_s)$$

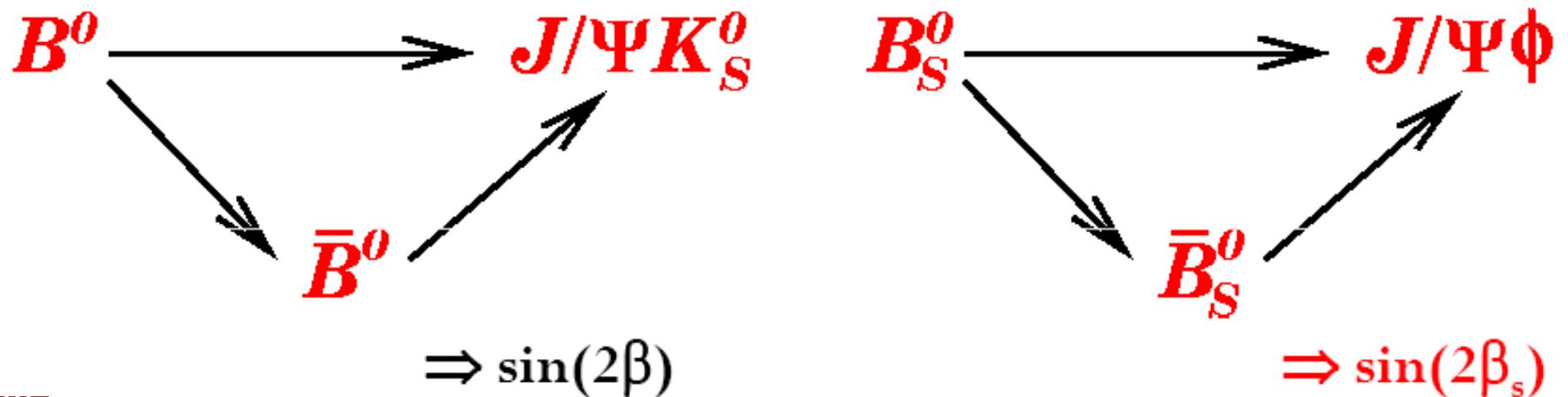
$$\phi_s^{\text{SM}} = \arg(-M_{12}/\Gamma_{12}) \approx 4 \times 10^{-3}$$

$$|B_{L,H}(t)\rangle = p |B_s^0\rangle \pm q |\overline{B}_s^0\rangle, q/p = \frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}}$$

CP Violation in $B_s^0 \rightarrow J/\psi\phi$



- From above diagrams, phase $\beta_s^{SM} = \arg(-V_{ts}^* V_{tb} / V_{cs}^* V_{cb}) \approx 0.02$
- CP violation occurs in the **interference of mixing and decay**
- This is in analogy to the well-studied case of $B_d^0 \rightarrow J/\psi K_S^0$



$$B_s^0 \rightarrow J/\psi \phi \text{ Vs. } B_d^0 \rightarrow J/\psi K_S^0$$

- Oscillation frequency $\Delta m_s \approx 35 \times \Delta m_d \rightarrow$ need vertex resolution
- $J/\psi \phi$ admixture of CP -even and odd \rightarrow need angular analysis
- $\sin(2\beta_s) \approx 0.05 \times \sin(2\beta)$ from SM \rightarrow much smaller effect

(a)



(b)

(c)

7-92

Unitarity triangles to common scale

• a: $V_{id} V_{is}^*$

• b: $V_{is} V_{ib}^*$

• c: $V_{id} V_{ib}^*$

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β_s , ϕ_s Notation

- $\beta_s^{SM} = \arg(-V_{ts}^* V_{tb} / V_{cs}^* V_{cb}) \approx 0.02$
 - phase of the $b \rightarrow c\bar{c}s$ transition that accounts for mixing & mixing + decay
- $\phi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \approx 0.004$
 - $\arg(M_{12}) = \arg[(V_{tb} V_{ts}^*)^2]$: connecting B_s^0 to \overline{B}_s^0 through oscillation
 - $\arg(\Gamma_{12}) = \arg[(V_{cb} V_{cs}^*)^2 + V_{cb} V_{cs}^* V_{ub} V_{us}^* + (V_{ub} V_{us}^*)^2]$: width of matter and antimatter into common final states

Both SM values too small for current experimental sensitivity (assumed zero).
If new physics occurs in mixing:

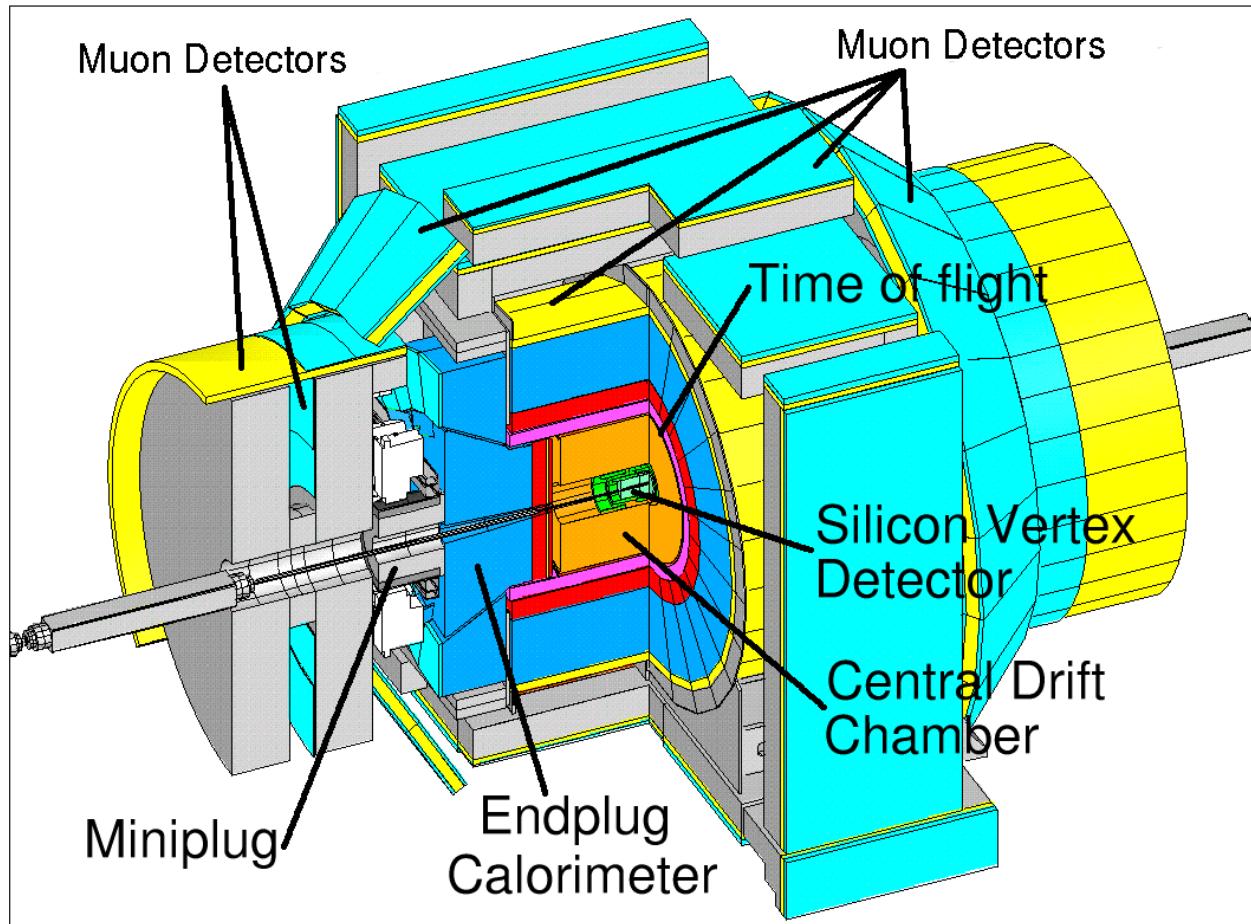
- $\phi_s = \phi_s^{SM} + \phi_s^{NP}$
- $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$

Standard shorthand $\rightarrow \phi_s = -2\beta_s$

Measurement

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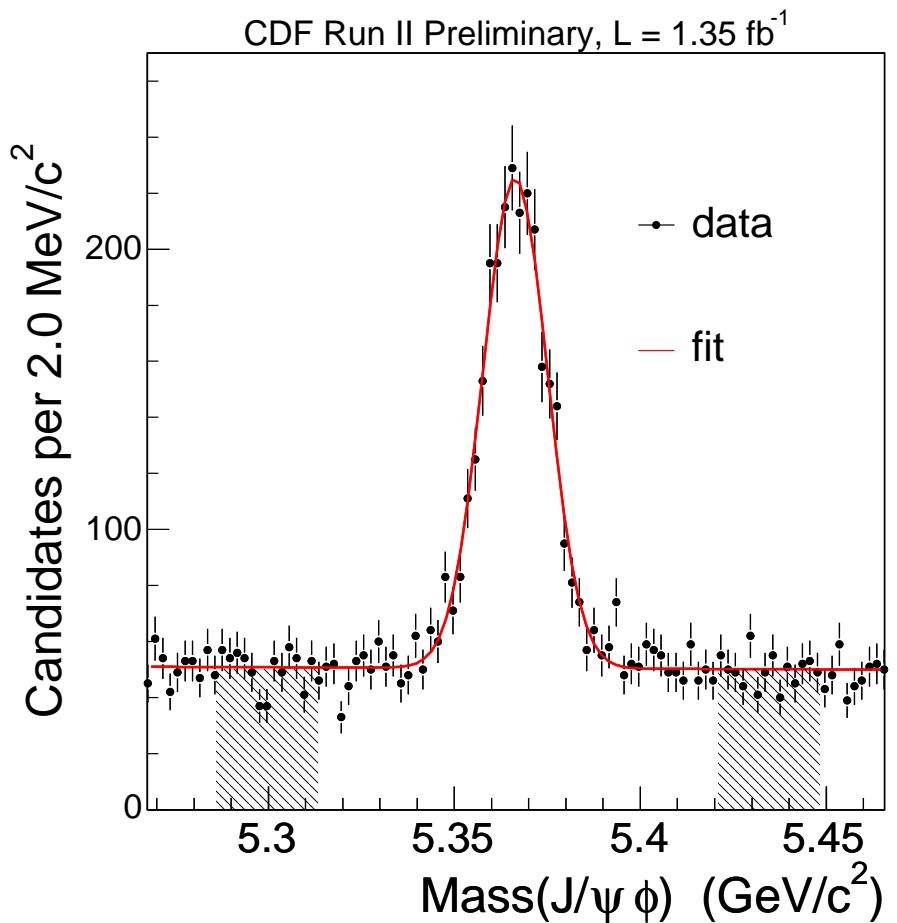
CDF Detector, B Physics Focus



- Silicon SVXII + Layer00:
 - B physics triggers
 - Vertex Resol $\approx 25\mu m$
- COT drift chamber:
 - Momentum resolution $\sigma_p/p^2 < 0.1\%$
 - dE/dx for particle ID (selection, tagging)
- Time-Of-Flight:
 - Particle ID (selection, tagging)
- Muon det., EM cal:
 - Lepton triggers
 - Lepton ID: tagging

Data Sample and Selection

- Data w/ $1.35\text{fb}^{-1}(1.7)$
- Di-muon trigger
- Soft precuts followed by neural network selection
- NN Trained on:
 - Simulated events for signal
 - B_s^0 mass sidebands for bkg
- Selection maximizes $S/\sqrt{S+B}$ in signal peak
- $S \approx 2000$ $B_s^0 \rightarrow J/\psi\phi$ signal evts
 $S/B \approx 2$ in signal peak



General Analysis Strategy

Reconstruct decays from stable products:

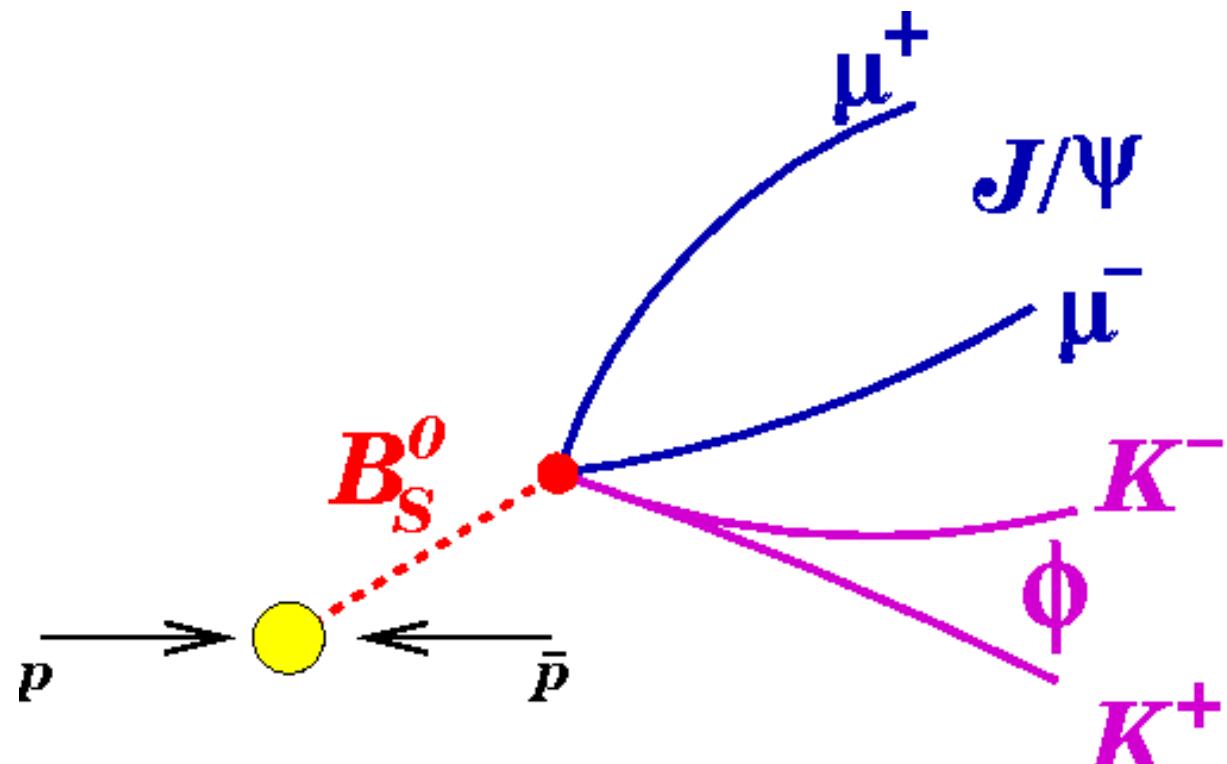
- $B_s^0 \rightarrow J/\psi [\mu^+ \mu^-] \phi [K^+ K^-]$
- $B_d^0 \rightarrow J/\psi [\mu^+ \mu^-] K^* [K^+ \pi^-]$
- $B_d^0 \rightarrow J/\psi K^*$: control sample

Identify $B_s^0/\overline{B_s^0}$

- Flavor tagging

Event variables:

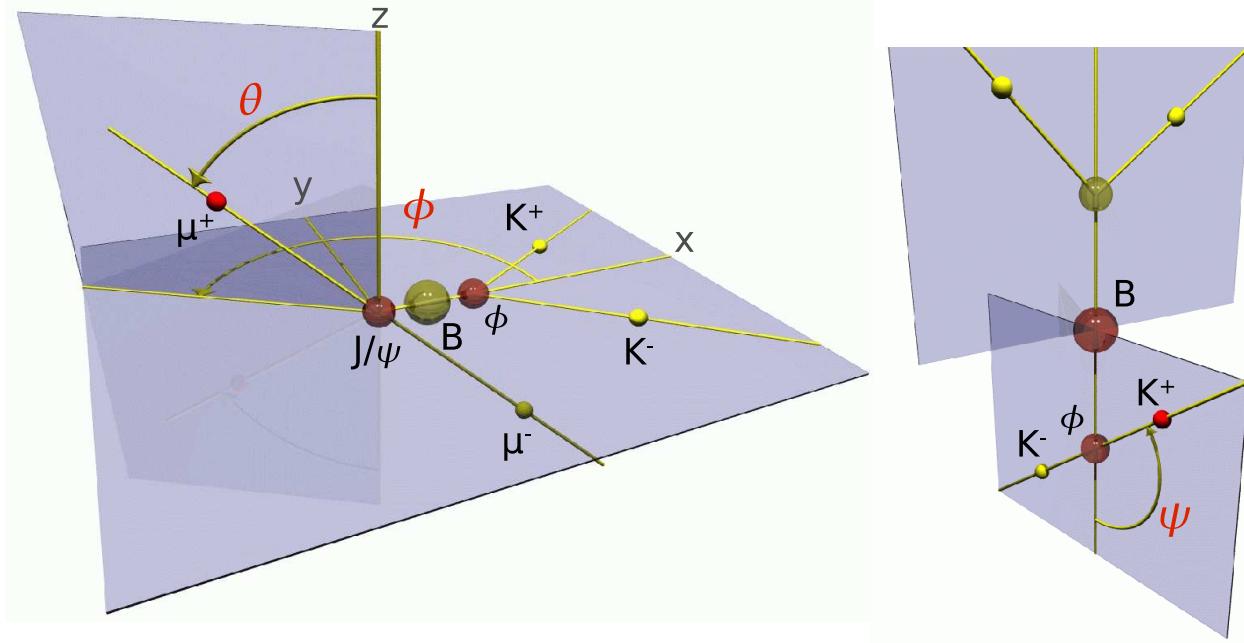
- Mass
- Lifetime $ct = m_B L_{xy}/p_T$
- $\vec{\rho} \equiv \theta_T, \phi_T, \psi_T$
- Tag decision ξ



Perform maximum likelihood fit:

- Likelihood in $m, ct, \vec{\rho}, \xi$

$B_s^0 \rightarrow J/\psi \phi$ Angular Analysis



Angular momentum:

- $P \rightarrow VV$ decay:
 - $L = 0$
 - $L = 1$
 - $L = 2$

Transversity Basis:

- Since $J/\psi\phi$ is C-odd, parity determines CP
- In Transversity basis, polarization of VV :
 - longitudinal (0), transverse and parallel (\parallel) $\rightarrow CP\text{-even}$
 - transverse and perpendicular (\perp) $\rightarrow CP\text{-odd}$

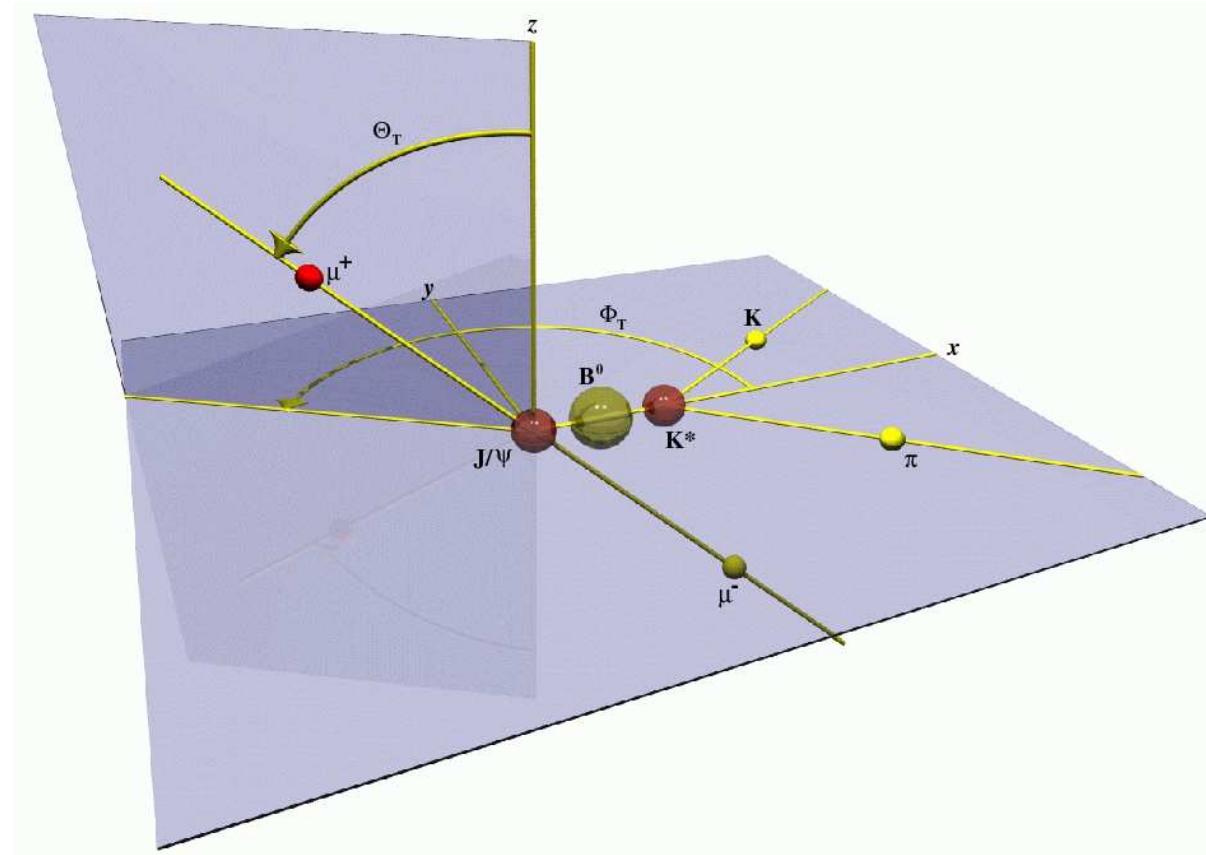
$B_d^0 \rightarrow J/\psi K^*$ Angular Analysis

Similar Angular Decay:

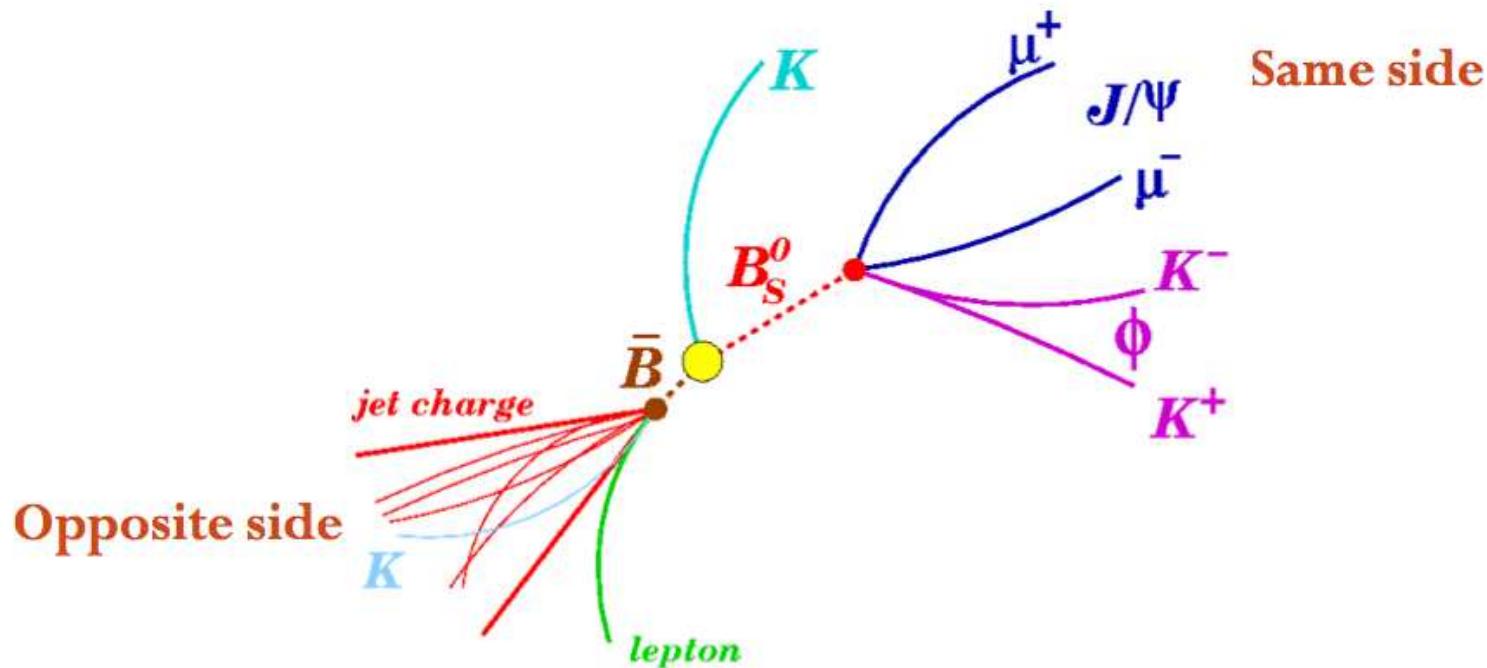
- $P \rightarrow VV$
- Similar phase space available

Control:

- Detector efficiency in \vec{p}
- Measure $|A_0|$, $|A_{||}|$, $|A_{\perp}|$



Flavor Tagging



- 2 independent methods of tagging: same and opposite side
- Opposite Side Tagger is calibrated using data (high stat B^+ , B_d^0)
- Same Side Tagger is calibrated on Monte Carlo
- Efficiency $\varepsilon = P(\text{tag decision})$
- Dilution $\mathcal{D} = 1 - 2q$, q is mistag probability

Opposite Side Flavor Tagging

Exclusive algorithms:

Soft Lepton Tagger

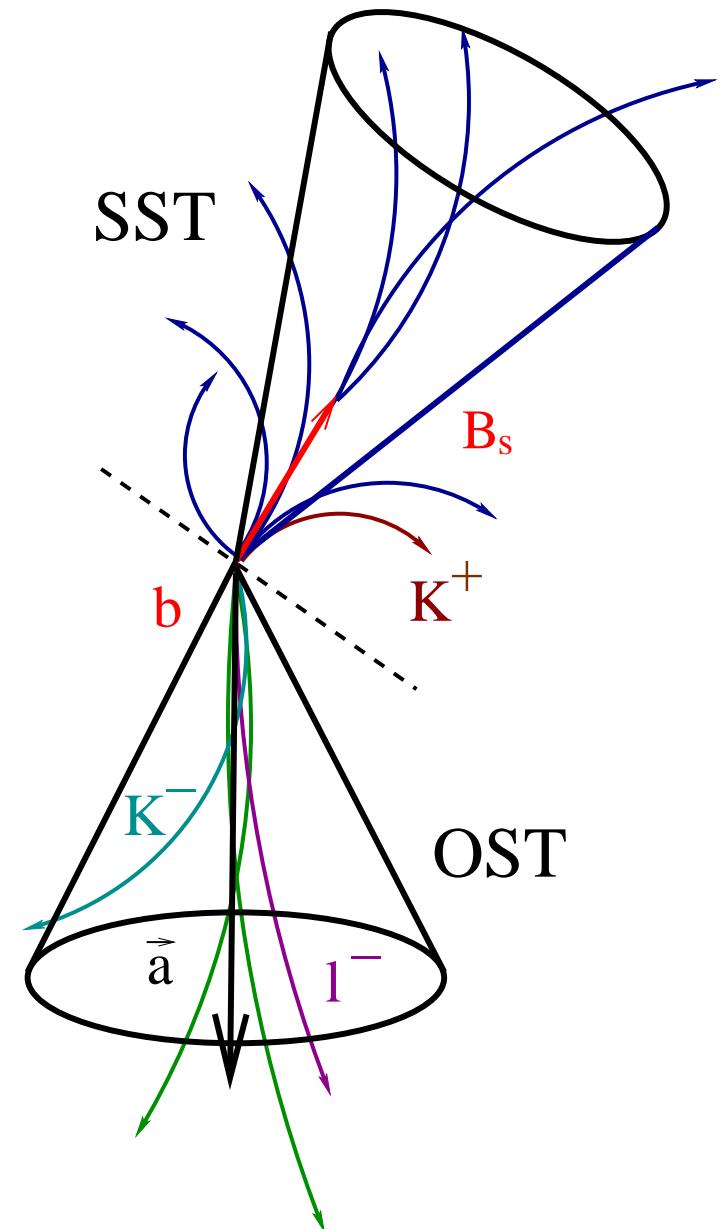
- look for semileptonic B decay on OS
- lepton charge indicates *b*-flavor
- μ , e tagger

Jet Charge Tagger

- look for jet or secondary vertex on OS
- jet charge indicates *b*-flavor

Performance

- Efficiency: $\epsilon = 0.96 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.11 \pm 0.02$



Same Side Flavor Tagging

Most Powerful Tagger:

Fragmentation Track

- Look for Kaon assoc. w/ B_s^0 production
- Use TOF & COT for $\pi - K$ separation

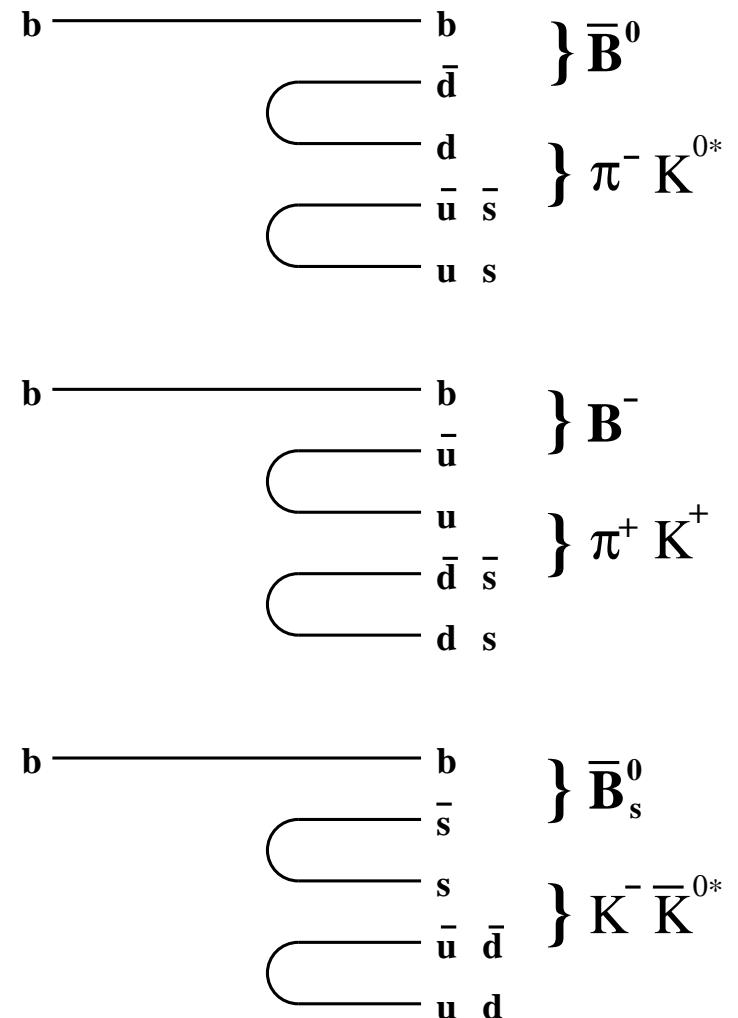
Calib using Monte Carlo

- B_s^0 , B_d^0 , B^+ different
- Use PYTHIA simulation

Performance

- Efficiency: $\varepsilon = 0.50 \pm 0.01$
- Avg Dilution: $\mathcal{D} = 0.27 \pm 0.04$

→ SST + OST Total $\varepsilon\mathcal{D}^2 \approx 4\%$



Likelihood for Decay to J/ ψ ϕ : Overview

$B_s^0/\overline{B}_s^0 \rightarrow J/\psi\phi$ differential decay rates depend on 4 event variables:

- ct : Proper decay length
- $\vec{\rho}$: vector formed by the 3 angles that characterize the decay
- ξ : tag decision ($+1 \rightarrow B_s^0$, $-1 \rightarrow \overline{B}_s^0$, $0 \rightarrow$ no tag)

... and quite a few parameters describing the physics

- $|A_\alpha|$, $\alpha = 0, \parallel, \perp$: amplitudes for decay to longitudinal, parallel (both CP -even), or perpendicular (CP -odd) polarizations of J/ψ , ϕ
- δ_α : Phases associated with those amplitudes
- $\Gamma, \Delta\Gamma$: Average lifetime and lifetime difference

$$P(ct, \vec{\rho} | \xi) = \frac{1 + \xi \mathcal{D}}{1 + |\xi|} \cdot P_B(ct, \vec{\rho}) + \frac{1 - \xi \mathcal{D}}{1 + |\xi|} \cdot P_{\overline{B}}(ct, \vec{\rho})$$

Likelihood for Decay to J/ ψ ϕ : Time Dependence

$$\frac{d^4 P(t, \vec{\rho})}{dtd\vec{\rho}} \propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_{||}|^2 T_+ f_2(\vec{\rho})$$

B^0_s term

$$+ |A_{\perp}|^2 T_- f_3(\vec{\rho}) + |A_{||}| |A_{\perp}| \mathcal{U}_+ f_4(\vec{\rho})$$

$$+ |A_0| |A_{||}| \cos(\delta_{||}) T_+ f_5(\vec{\rho})$$

$$+ |A_0| |A_{\perp}| \mathcal{V}_+ f_6(\vec{\rho}),$$

$A_0, A_{||}, A_{\perp}$: transition amplitudes in a given polarization state

$$\frac{d^4 \bar{P}(t, \vec{\rho})}{dtd\vec{\rho}} \propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_{||}|^2 T_+ f_2(\vec{\rho})$$

anti- B^0_s

$$+ |A_{\perp}|^2 T_- f_3(\vec{\rho}) + |A_{||}| |A_{\perp}| \mathcal{U}_- f_4(\vec{\rho})$$

$$+ |A_0| |A_{||}| \cos(\delta_{||}) T_+ f_5(\vec{\rho})$$

$$+ |A_0| |A_{\perp}| \mathcal{V}_- f_6(\vec{\rho}),$$

$f(\vec{\rho})$: angular distribution for a given polarization state

CP-Violating Terms

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta\Gamma t/2) \\ \mp \eta \sin(2\beta_s) \sin(\underline{\Delta m_s} t)] ,$$

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_\parallel) \cos(\underline{\Delta m_s} t) \\ - \cos(\delta_\perp - \delta_\parallel) \cos(2\beta_s) \sin(\underline{\Delta m_s} t) \\ \pm \cos(\delta_\perp - \delta_\parallel) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)] ,$$

$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp) \cos(\underline{\Delta m_s} t) \\ - \cos(\delta_\perp) \cos(2\beta_s) \sin(\underline{\Delta m_s} t) \\ \pm \cos(\delta_\perp) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)] .$$

$$\delta_\perp = \arg[A_\perp^* A_0] , \delta_\parallel = \arg[A_\parallel^* A_0]$$

Fit without Tagging

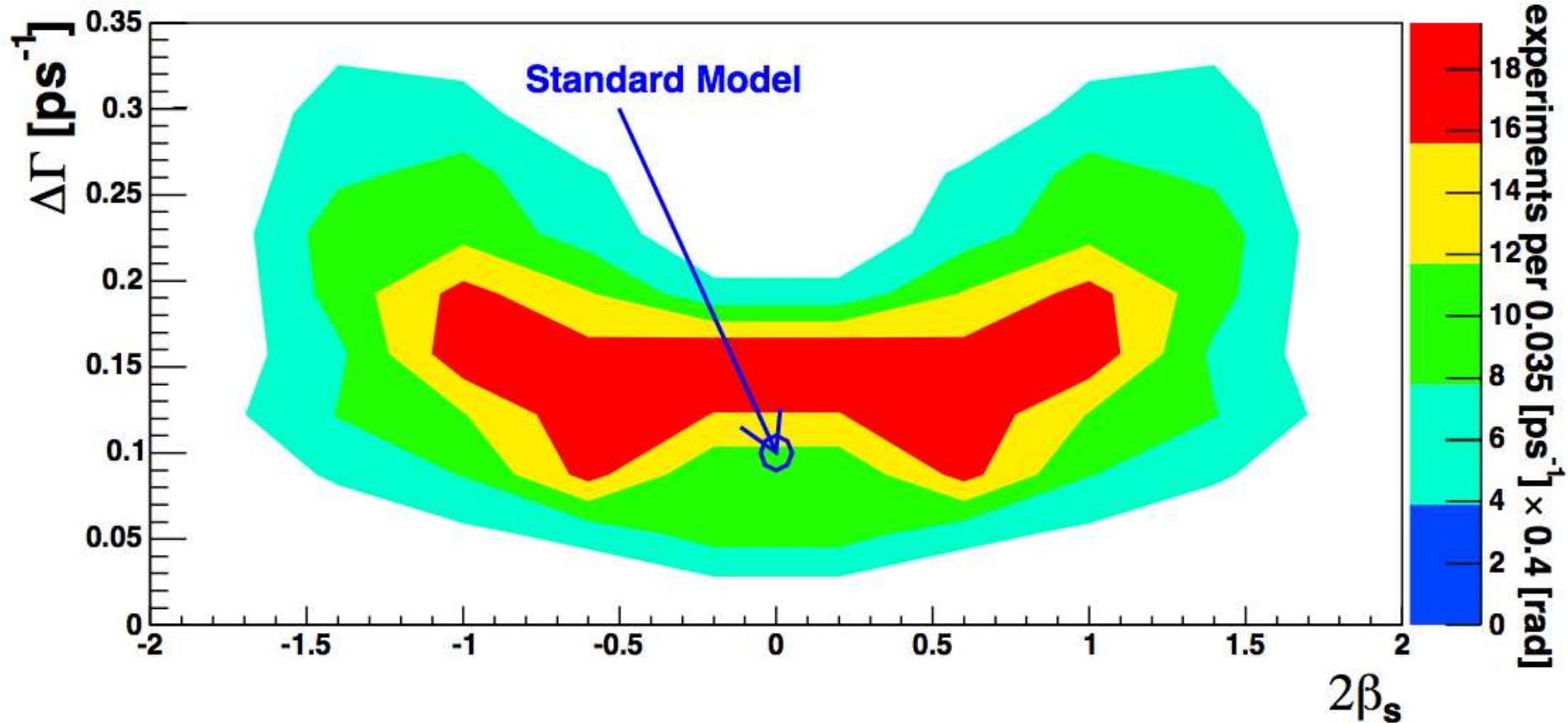
$$T_{\pm} = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta\Gamma t/2) \\ \mp \eta \sin(2\beta_s) \sin(\Delta m_s t)],$$

$$U_{\pm} = \pm e^{-\Gamma t} \times [\sin(\delta_{\perp} - \delta_{\parallel}) \cos(\Delta m_s t) \\ - \cos(\delta_{\perp} - \delta_{\parallel}) \cos(2\beta_s) \sin(\Delta m_s t) \\ \pm \cos(\delta_{\perp} - \delta_{\parallel}) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)],$$

$$V_{\pm} = \pm e^{-\Gamma t} \times [\sin(\delta_{\perp}) \cos(\Delta m_s t) \\ - \cos(\delta_{\perp}) \cos(2\beta_s) \sin(\Delta m_s t) \\ \pm \cos(\delta_{\perp}) \sin(2\beta_s) \sinh(\Delta\Gamma t/2)].$$

Some sensitivity to β_s , but better suited to measure $\Delta\Gamma$, $c\tau$

Fit Difficulties (Tagging Turned Off)



- Monte Carlo study with $\Delta\Gamma - \beta_s$ generated at SM values
- Plotting results of 300 fits in 2D plane

Source of Problems in Straightforward Fit

Difficulties arise

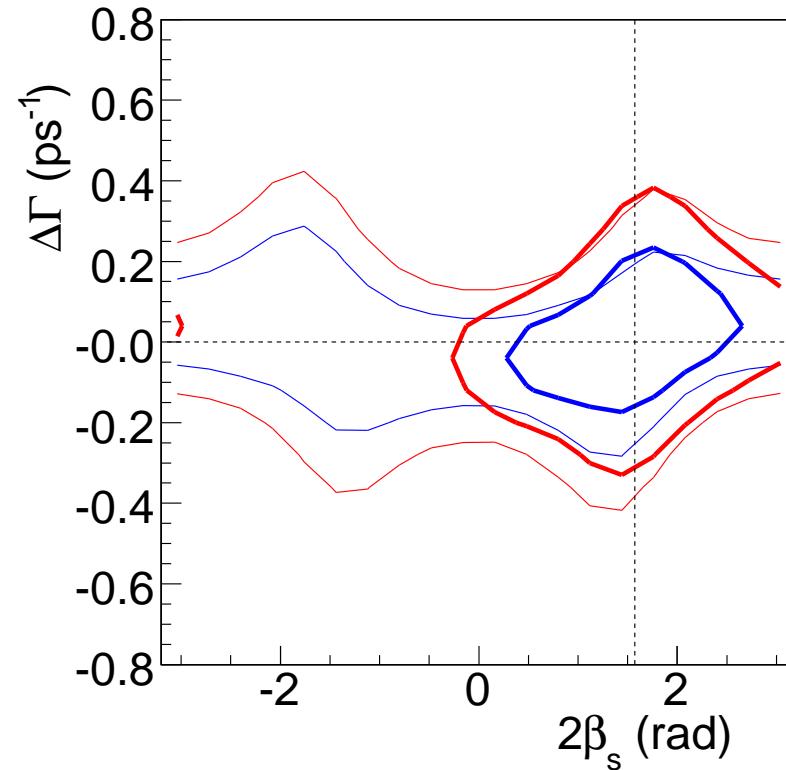
- Likelihood exhibits symmetry to following transformation:
 - $2\beta_s \rightarrow \pi - 2\beta_s$
 - $\Delta\Gamma \rightarrow -\Delta\Gamma$
 - $\delta_{||} \rightarrow 2\pi - \delta_{||}$
 - $\delta_{\perp} \rightarrow \pi - \delta_{\perp}$
- Small $\beta_s \rightarrow$ effective loss of degrees of freedom
 - Biases in straightforward likelihood fit (parameter-dependent)
 - Irregular (non-elliptical) likelihood shape & uncertainties
 - → Undercoverage by likelihood profile
- These problems go away with very large statistics, but not for our sensitivity

Effect of Flavor Tagging on Symmetries, etc

Separate time evolution of mesons produced as B_s^0 or \bar{B}_s . Utility:

Three ways to think of utility of flavor-tagging:

- In short: B_s^0/\bar{B}_s differential decay rates $\frac{dP}{dt d\vec{p}}(t, \vec{p})$ dependent on β_s differently
- Likelihood: with tagging, gain sensitivity to both $|\cos(2\beta_s)|$ and $|\sin(2\beta_s)|$, rather than only $|\cos(2\beta_s)|$ and $|\sin(2\beta_s)|$ (note absolute value)
- Visually: MC study comparing 68%, 95% likelihood contours for tagged(thick line) /untagged(thin line) in $\Delta\Gamma - \beta_s$ plane



2D confidence Region Method

- Problems arise from limited sensitivity: biases observed in pseudo-experiments depending on input value of β_s
- We use a likelihood ordering suggested by Feldman and Cousins to estimate a confidence interval
- Calculate a p-value for each point on the $\Delta\Gamma - \beta_s$ plane
- Verify that we have proper coverage in the confidence region for alternative true values of the parameters
- Construct a confidence region rather than quote a point estimate

Systematic Effects

→ Important for measurement of $\Delta\Gamma$, $c\tau$:

- $B_d^0 \rightarrow J/\psi K^*$ decays misreconstructed as B_s^0 : $O(3\%)$ contamination
- Signal mass model
- Lifetime resolution model
- Detector angular acceptance
- Silicon detector alignment

Tagged β_s result:

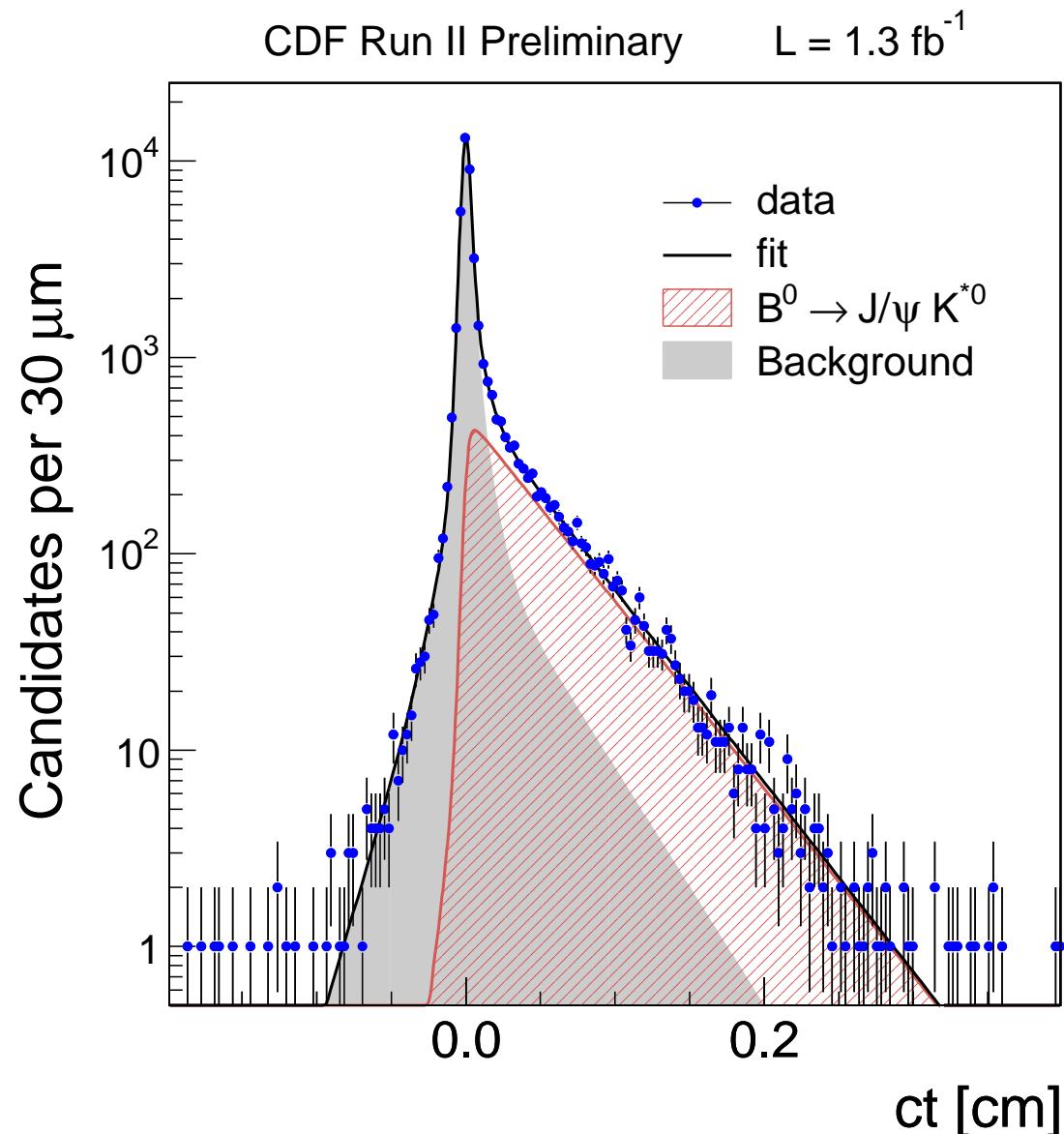
- Dilution scale factor
- Background angular distributions
- Lifetime resolution model/ bkg model

→ Contributed to 2% confidence region adjustment for $\Delta\Gamma - \beta_s$ result

Results

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B_d^0 Results: $c\tau$, Angular Parameters



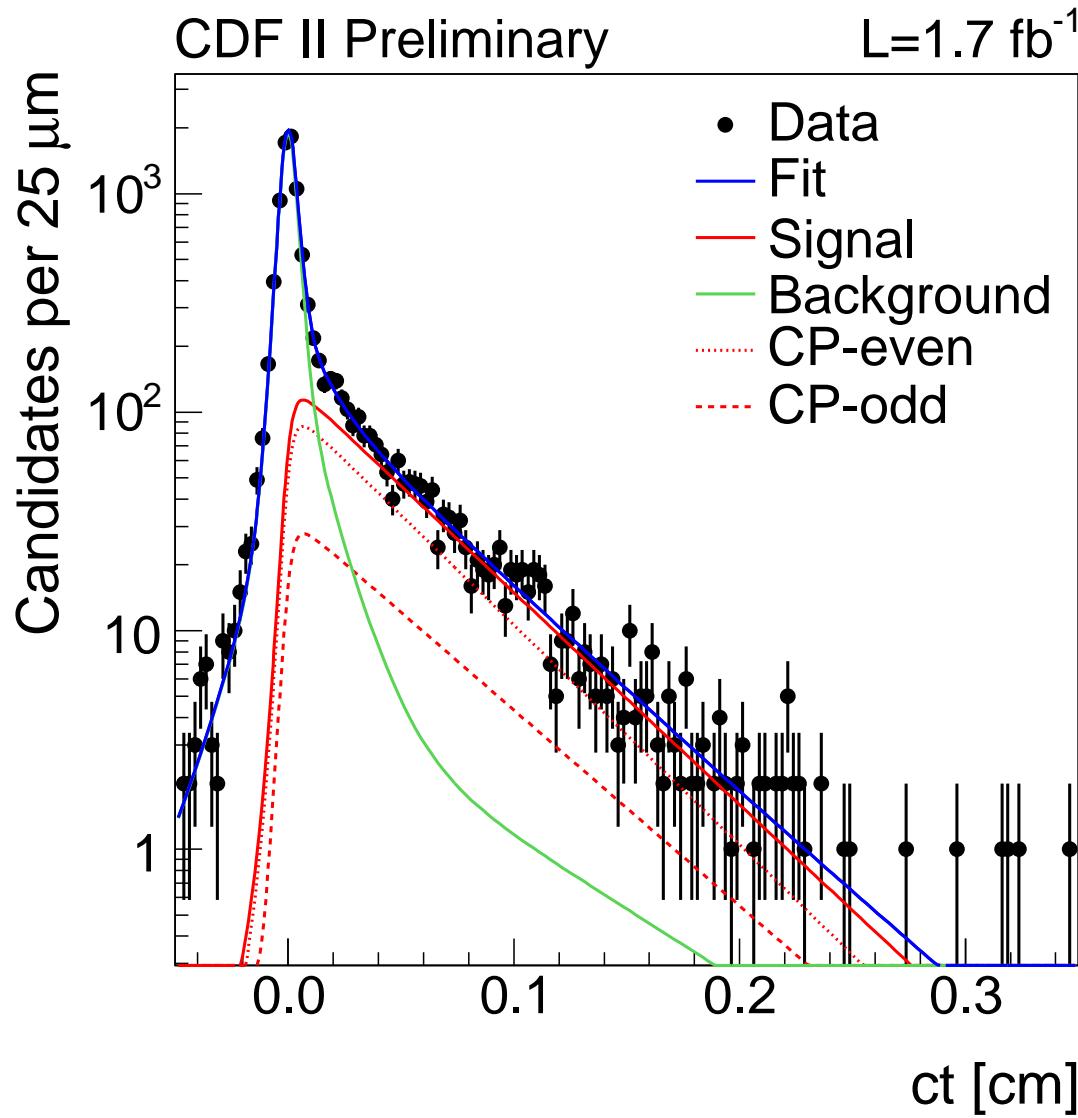
$$\text{Param} = \text{Val} \pm \text{Stat} \pm \text{Syst}$$

- $c\tau = 456 \pm 6 \pm 6 \mu\text{m}$
- $|A_0|^2 = 0.569 \pm 0.009 \pm 0.009$
- $|A_{\parallel}|^2 = 0.211 \pm 0.012 \pm 0.006$
- $\delta_{\parallel} = -2.97 \pm 0.08 \pm 0.03$
- $\delta_{\perp} = +2.97 \pm 0.06 \pm 0.01$

BaBar 2007 (hep-ex 0704.0522)

- $|A_0|^2 = 0.556 \pm 0.009 \pm 0.010$
- $|A_{\parallel}|^2 = 0.211 \pm 0.010 \pm 0.006$
- $\delta_{\parallel} = -2.93 \pm 0.08 \pm 0.04$
- $\delta_{\perp} = +2.91 \pm 0.05 \pm 0.03$

B_s^0 Untagged Results: $\Delta\Gamma$, $c\tau$



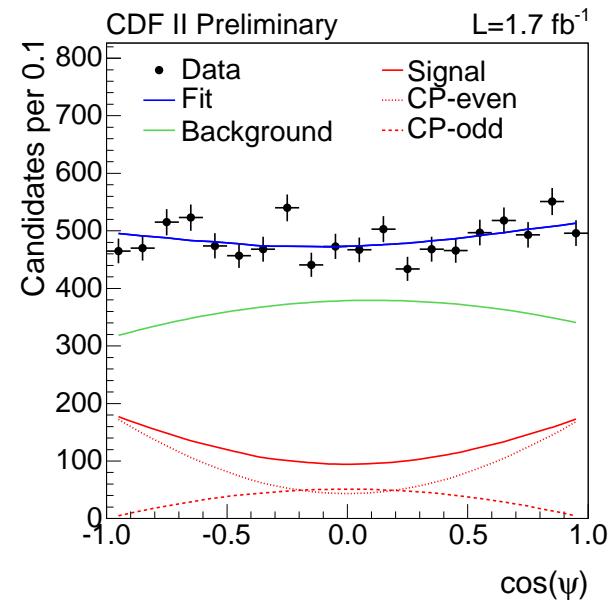
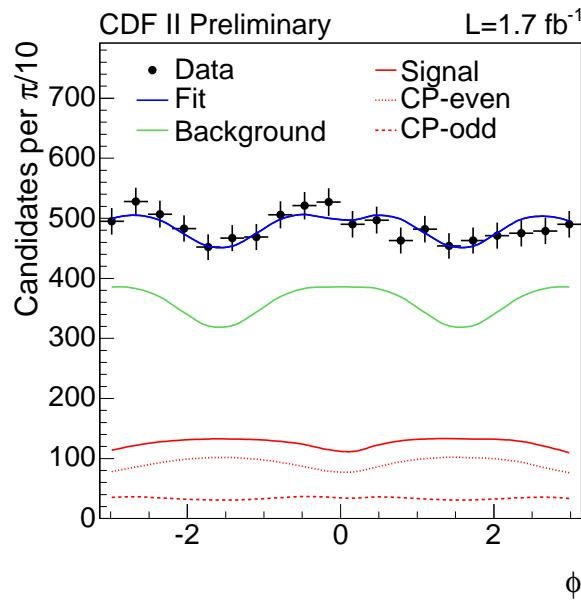
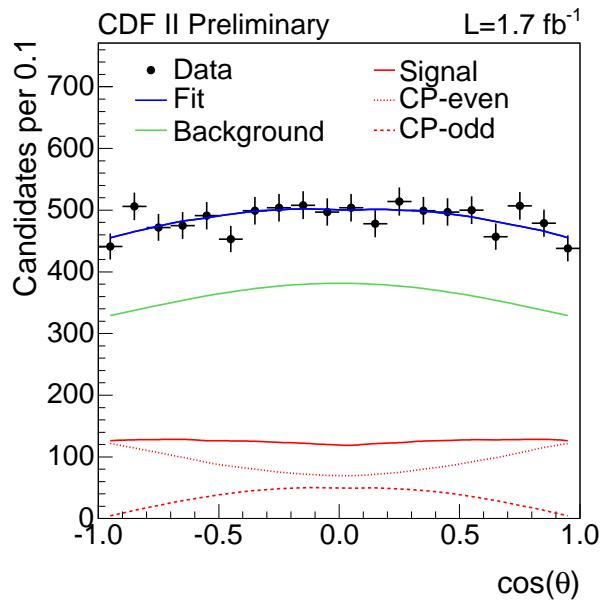
Fixing β_s to 0:

Param = Val \pm Stat \pm Syst

- $c\tau = 456 \pm 13 \pm 7 \mu\text{m}$
- $\Delta\Gamma = 0.076^{+0.059}_{-0.063} \pm 0.006 \text{ ps}^{-1}$

→ Improved best measurement
by 30 (50)%

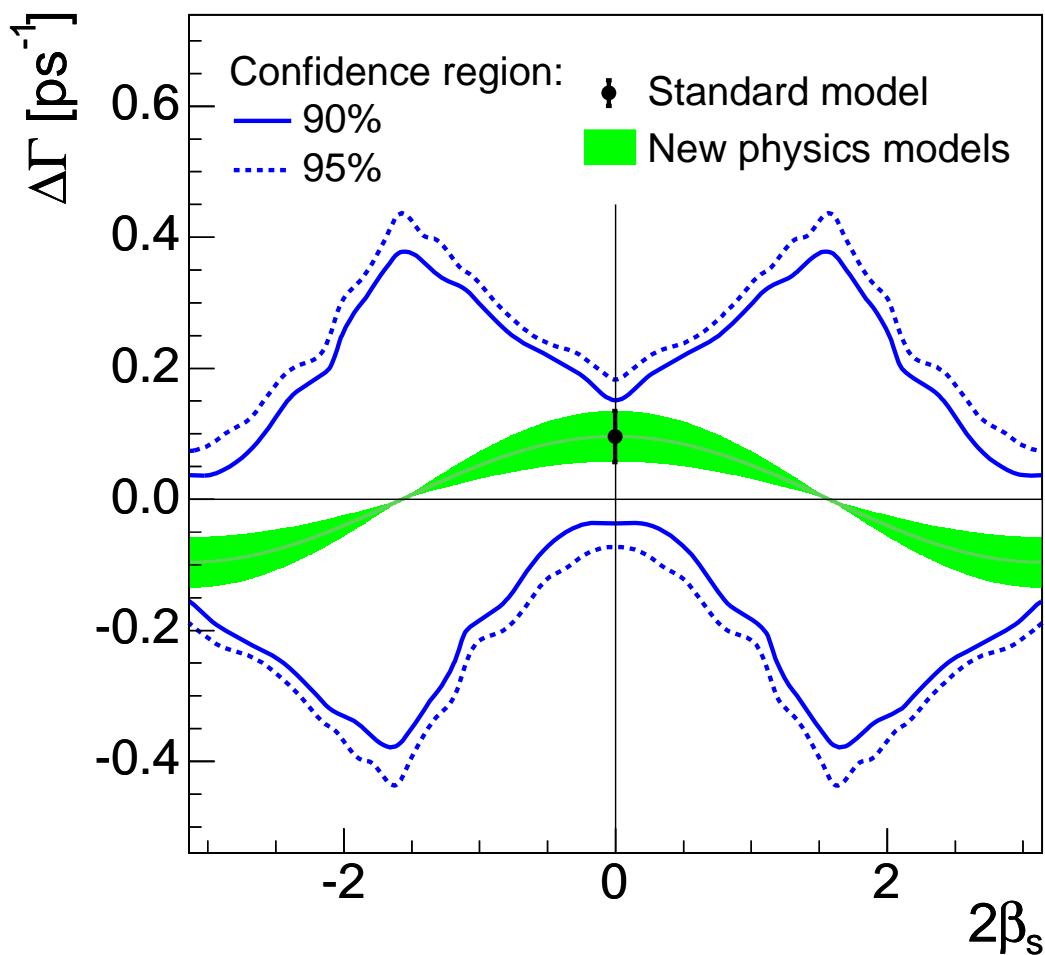
B_s^0 Untagged Results: Angular Parameters



Fixing β_s to 0:

- $|A_0|^2 = 0.531 \pm 0.020 \pm 0.007$
- $|A_{||}|^2 = 0.239 \pm 0.029 \pm 0.011$
- $|A_{\perp}|^2 = 0.230 \pm 0.026 \pm 0.009$

Untagged Results: $\Delta\Gamma - \beta_s$ Confidence Region



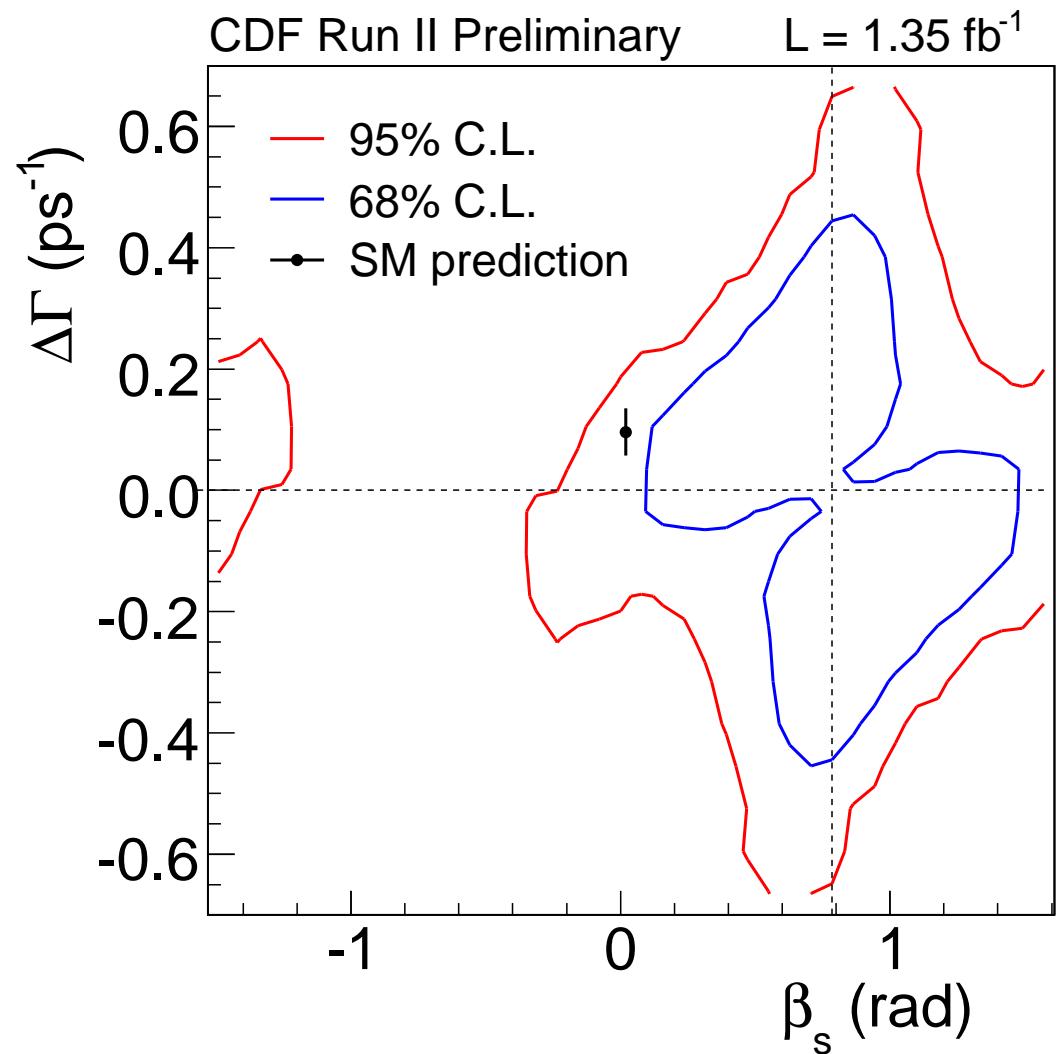
β_s Floating:

- Assuming the SM, the probability to observe a fluctuation as large or larger than the one observed in data: 22%

Tagged Results: $\Delta\Gamma - \beta_s$ F-C Confidence Region

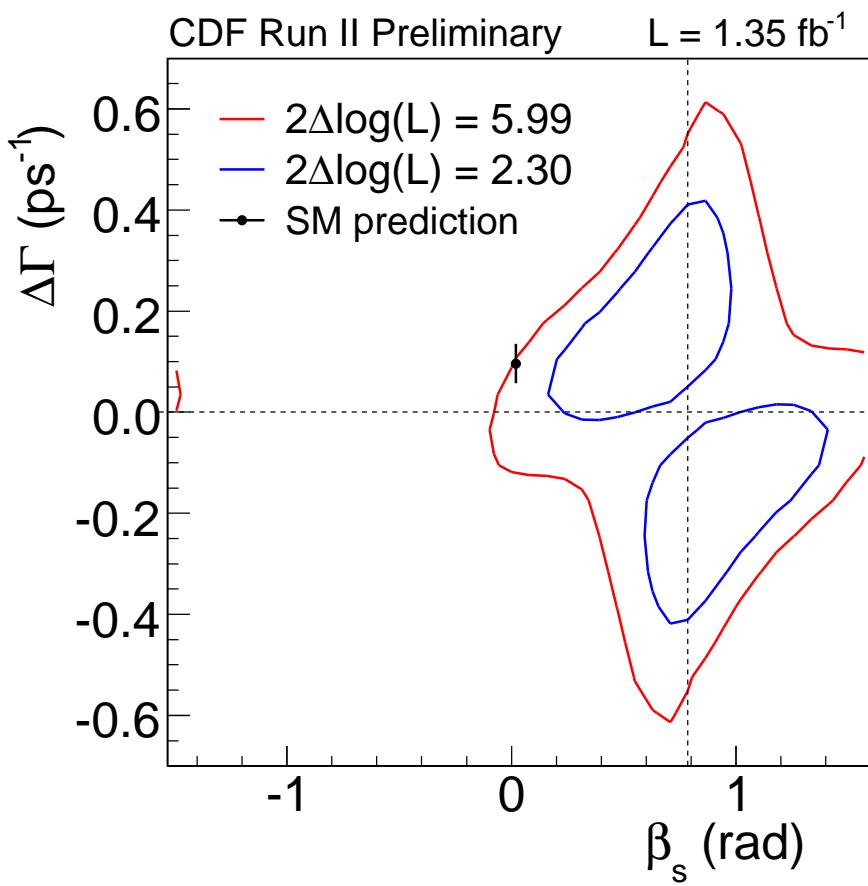
- Main result w/ tagging
- Assuming the SM, the probability to observe a fluctuation as large as or larger than the one observed in data:
15%, ($\approx 1.5\sigma$)
- $\cos(\delta_{\perp}) < 0$
 $\cos(\delta_{\perp} - \delta_{\parallel}) > 0$
in upper region
- $\cos(\delta_{\perp}) > 0$
 $\cos(\delta_{\perp} - \delta_{\parallel}) < 0$
in lower region

F-C Confidence Region:

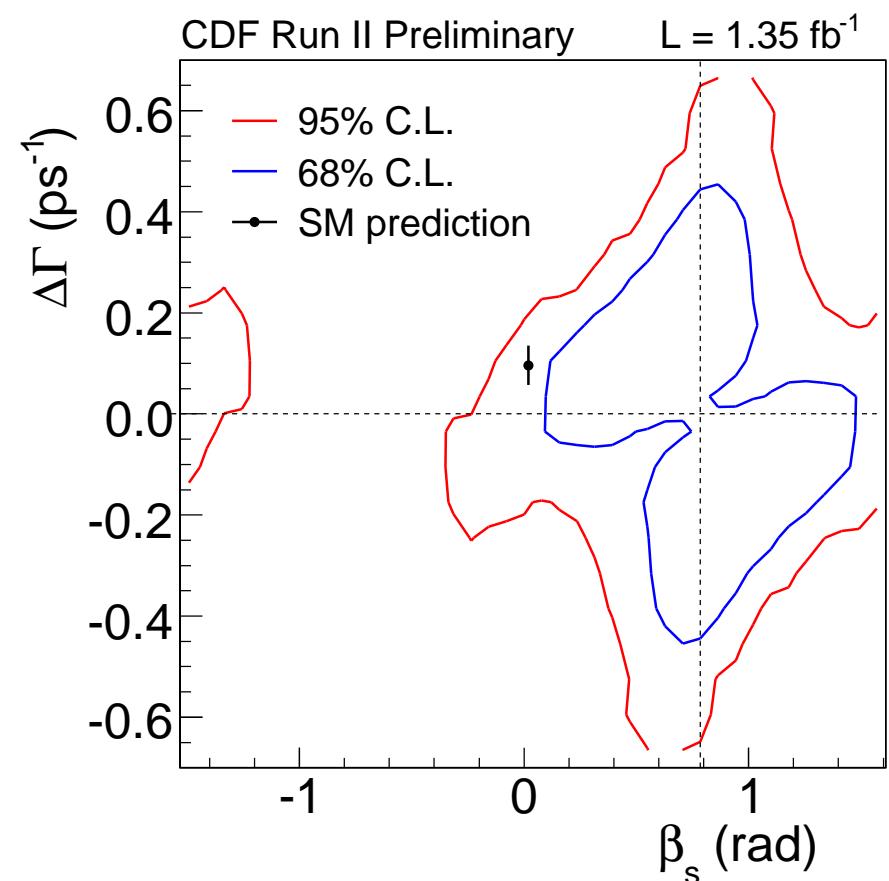


Tagged Results: Likelihood & F-C Confidence Region

Likelihood Profile:



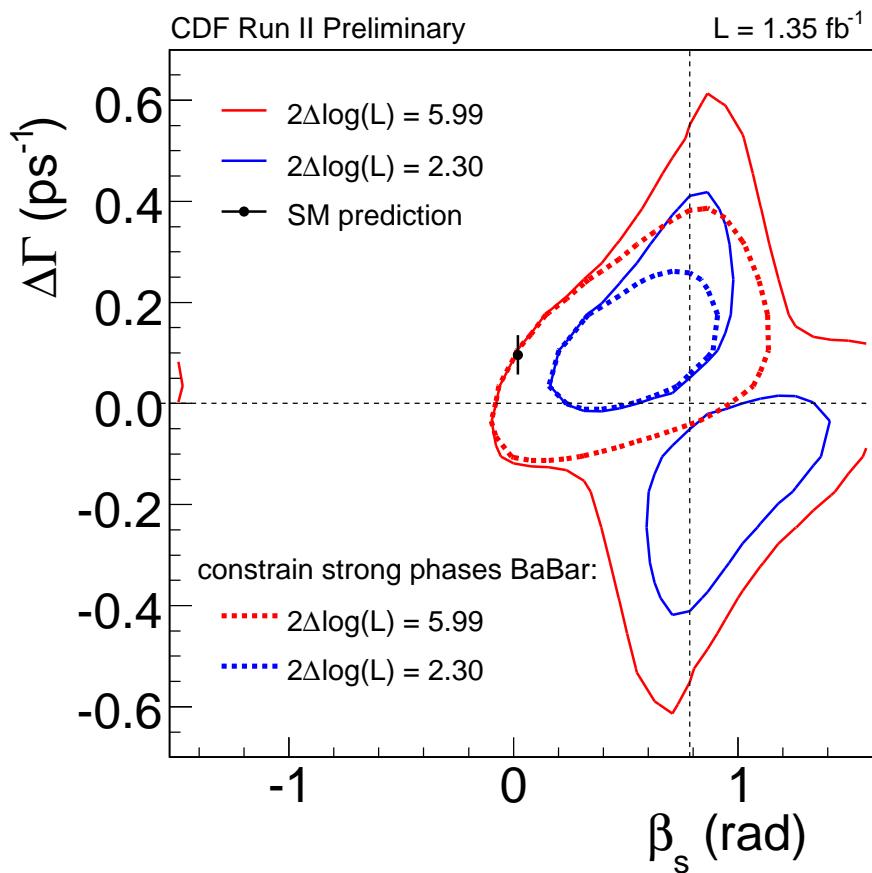
F-C Confidence Region:



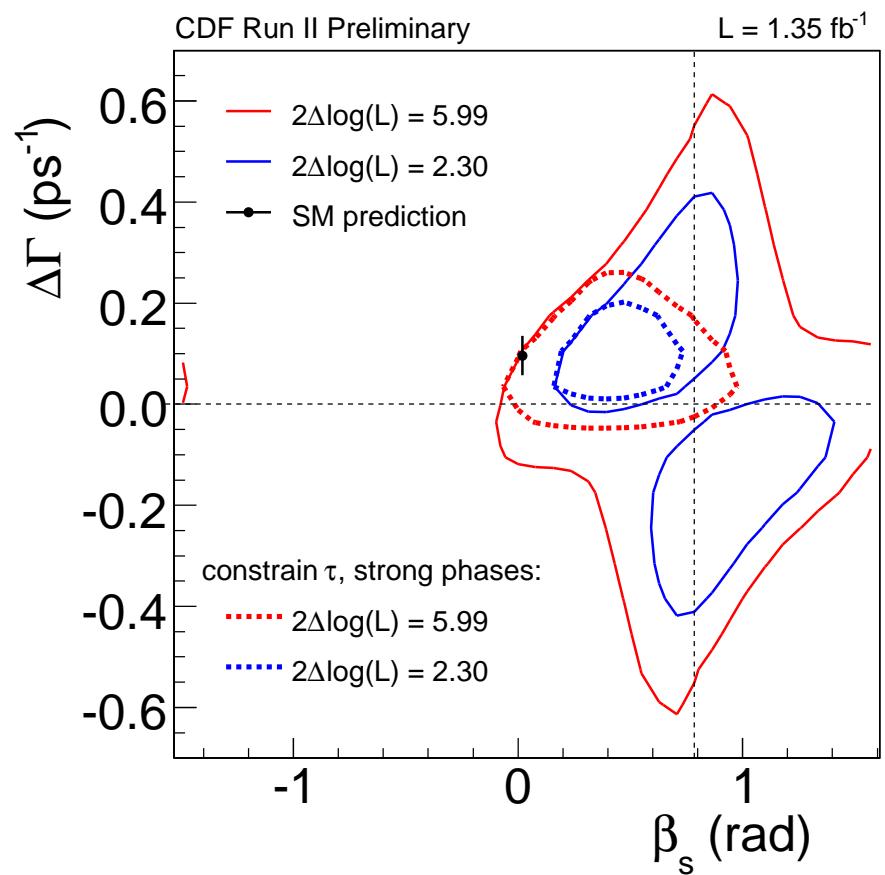
- “Similar” shape with likelihood profile, but F-C region has proper coverage

Tagged Results: β_s with Experimental Constraints

Strong Phases Constrained:



Phases & Lifetime (to $B_d^0 c\tau$):



- Constrained to BaBar results
in $B_d^0 \rightarrow J/\psi K^*$

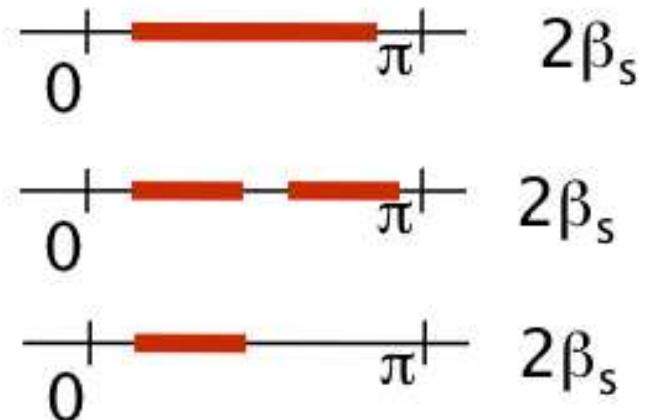
Results for β_s : 1-D Confidence Interval, Constraints

If we seek no info on $\Delta\Gamma$, bounding β_s in 1D:

- At 68% C.L. we find $2\beta_s \in [0.32, 2.82]$

Using a theoretical constraint on $|\Gamma_{12}|$:

- $2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$ at 68% C.L.

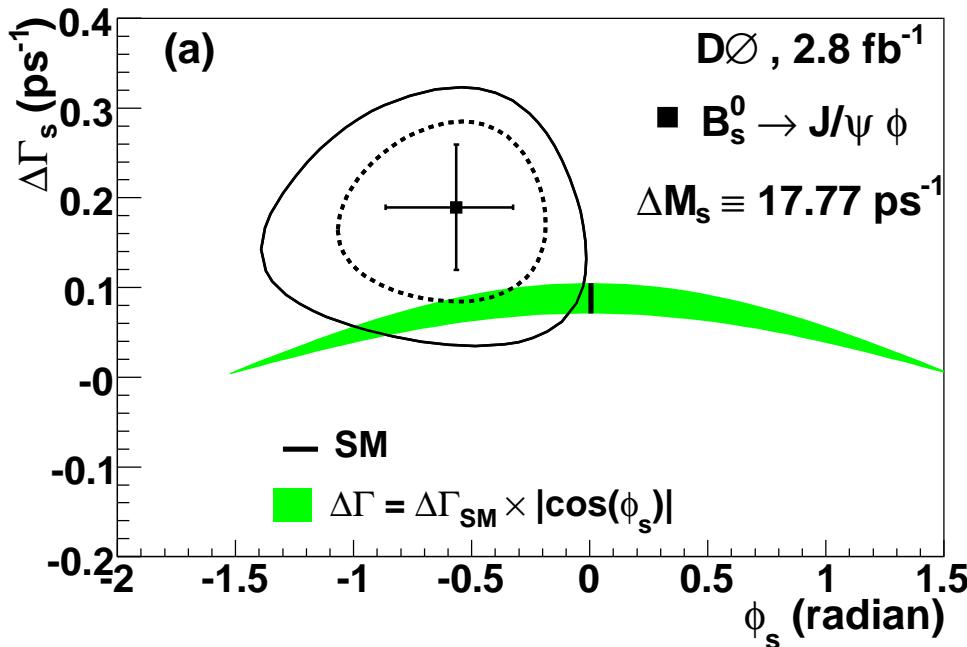


Adding constraint on $\delta_{||}$, δ_{\perp} from B factories:

- $2\beta_s \in [0.40, 1.20]$ at 68% C.L.

The latter range is the tightest constraint we can obtain on β_s incorporating all available information

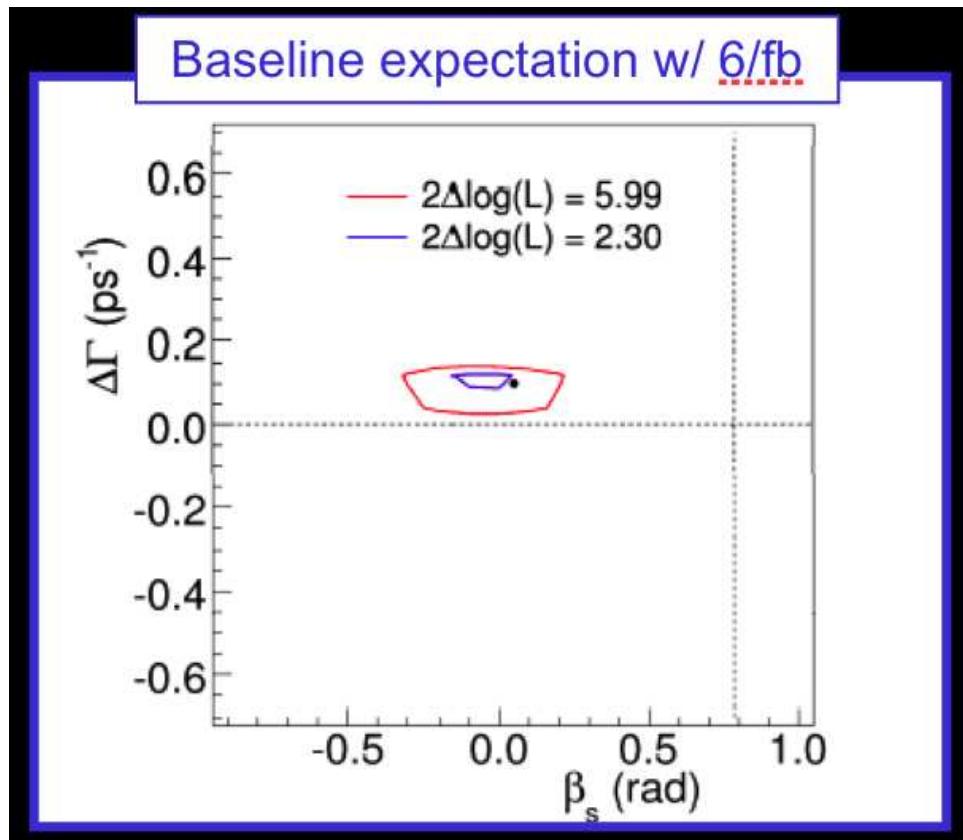
Latest D0 Result This Week: hep-ex 0802.2255



- $\Delta\Gamma = 0.19 \pm 0.07(\text{stat})^{+0.02}_{-0.01} (\text{syst}) \text{ ps}^{-1}$
- $\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})^{+0.07}_{-0.02} (\text{syst})$

Main result is point estimate with strong phases constrained. Best to compare to CDF's 1D confidence interval with similar constraint: $2\beta_s \in [0.40, 1.20]$ at 68% C.L.

Future Prospects



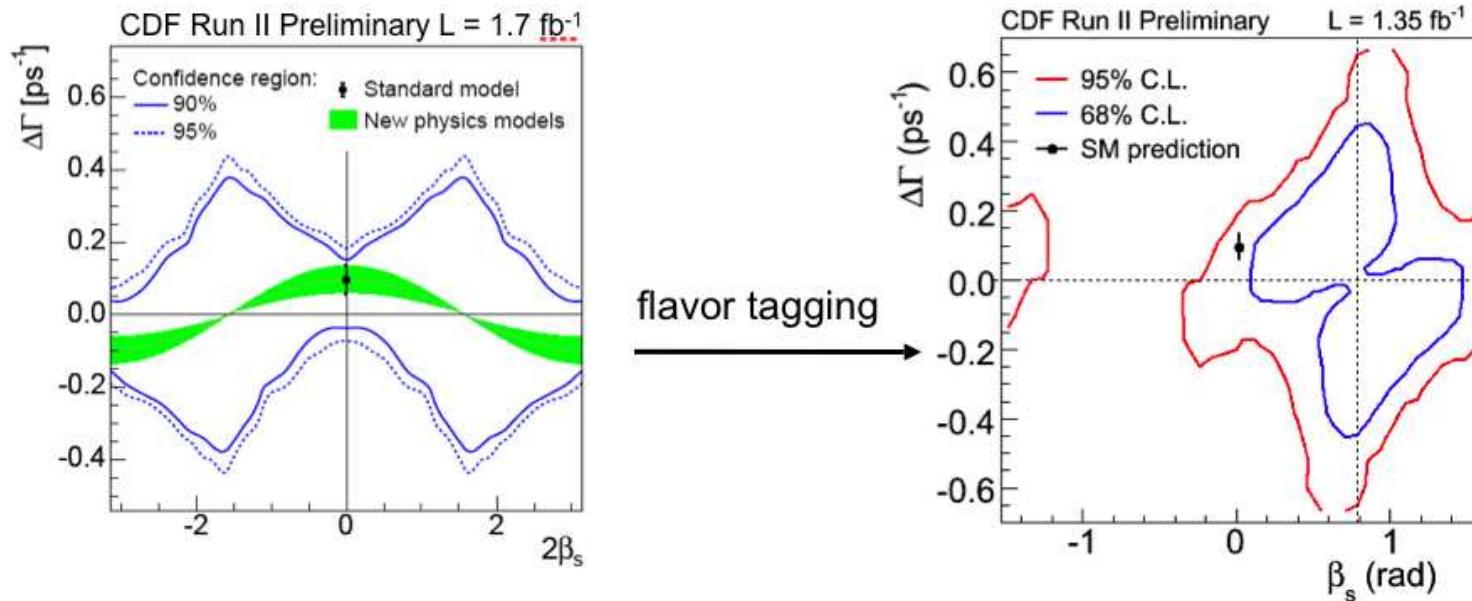
- Add +50% statistics from other triggers
- Improve tagging algorithms
- Better-behaved likelihood profile at high stat

This measurement will be a key component of the LHCb program. The Tevatron will have much more to say about it as well before “handing it over” to LHC.

Conclusion

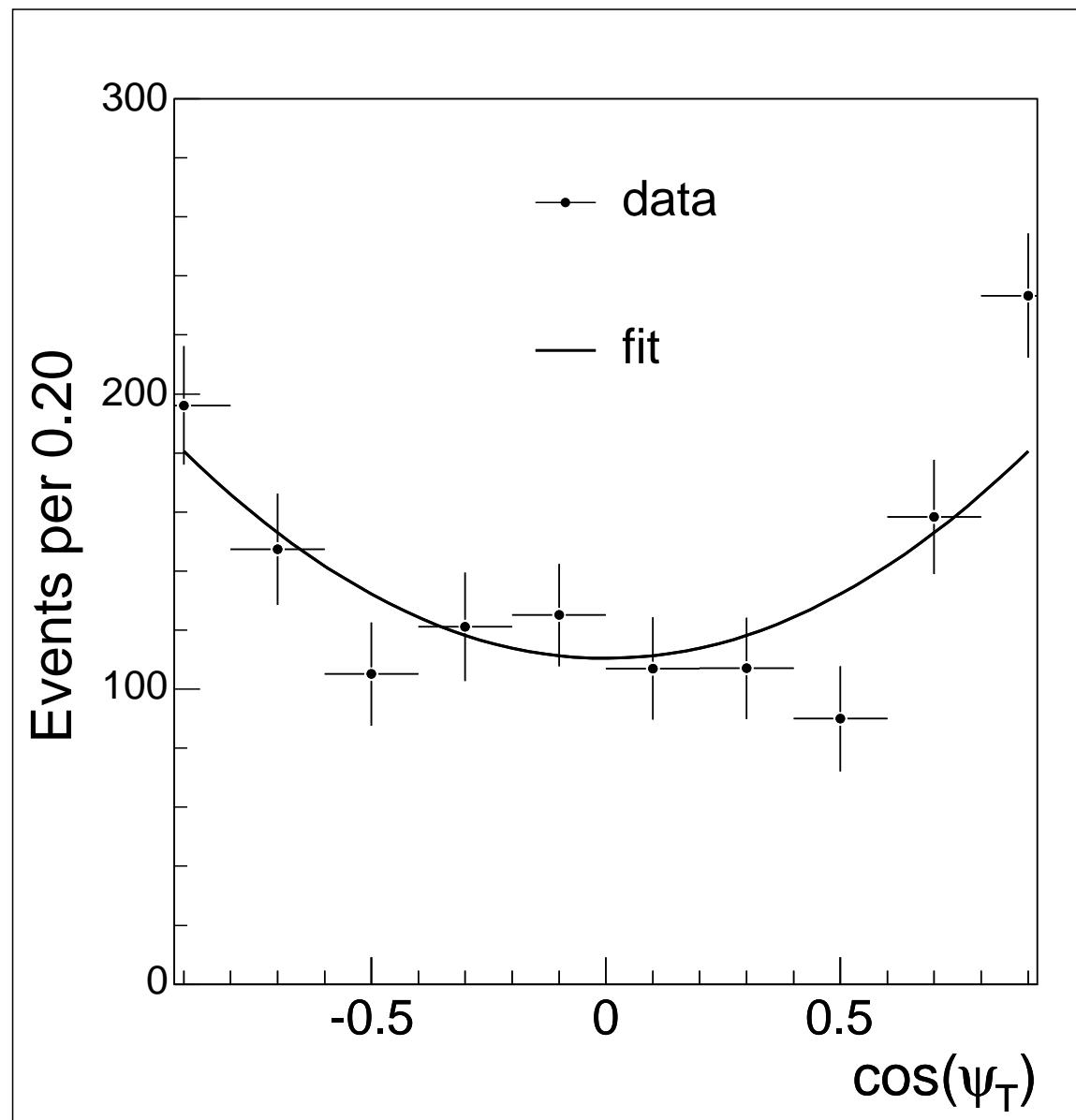
Important result in B physics:

- First flavor-tagged measurement of CP violating phase in B_s^0 system: submitted to PRL arXiv:0712.2397 [hep-ex]
- Cut in half allowed space of parameters. Already 95% CL exclusion of a large portion of the NP-phase space as allowed by global fits. Large positive values of ϕ_s excluded
- World's best determination of B_s^0 average lifetime and decay-width difference. Accepted by PRL arXiv:0712.2348 [hep-ex]

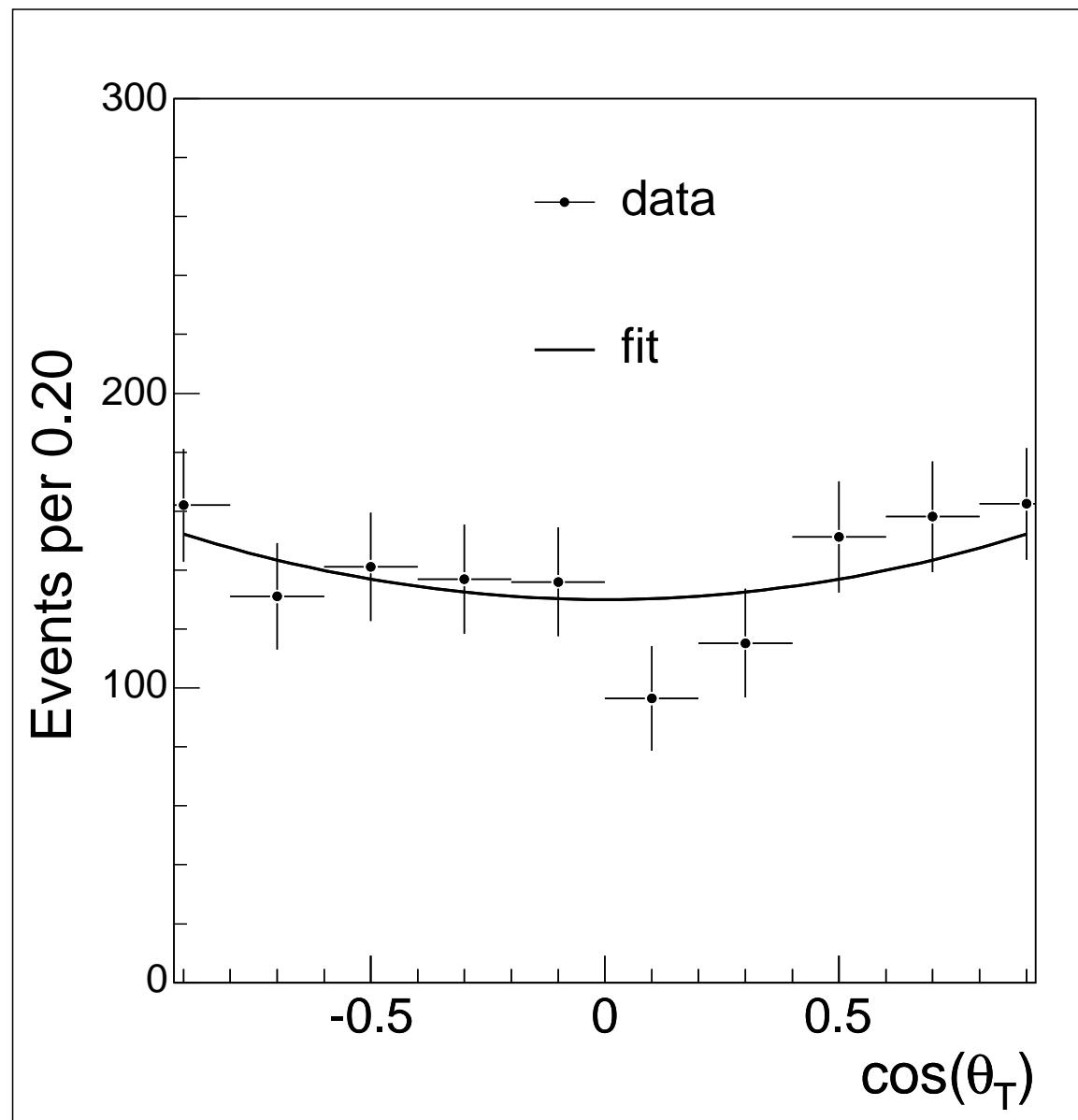


Additional Slides

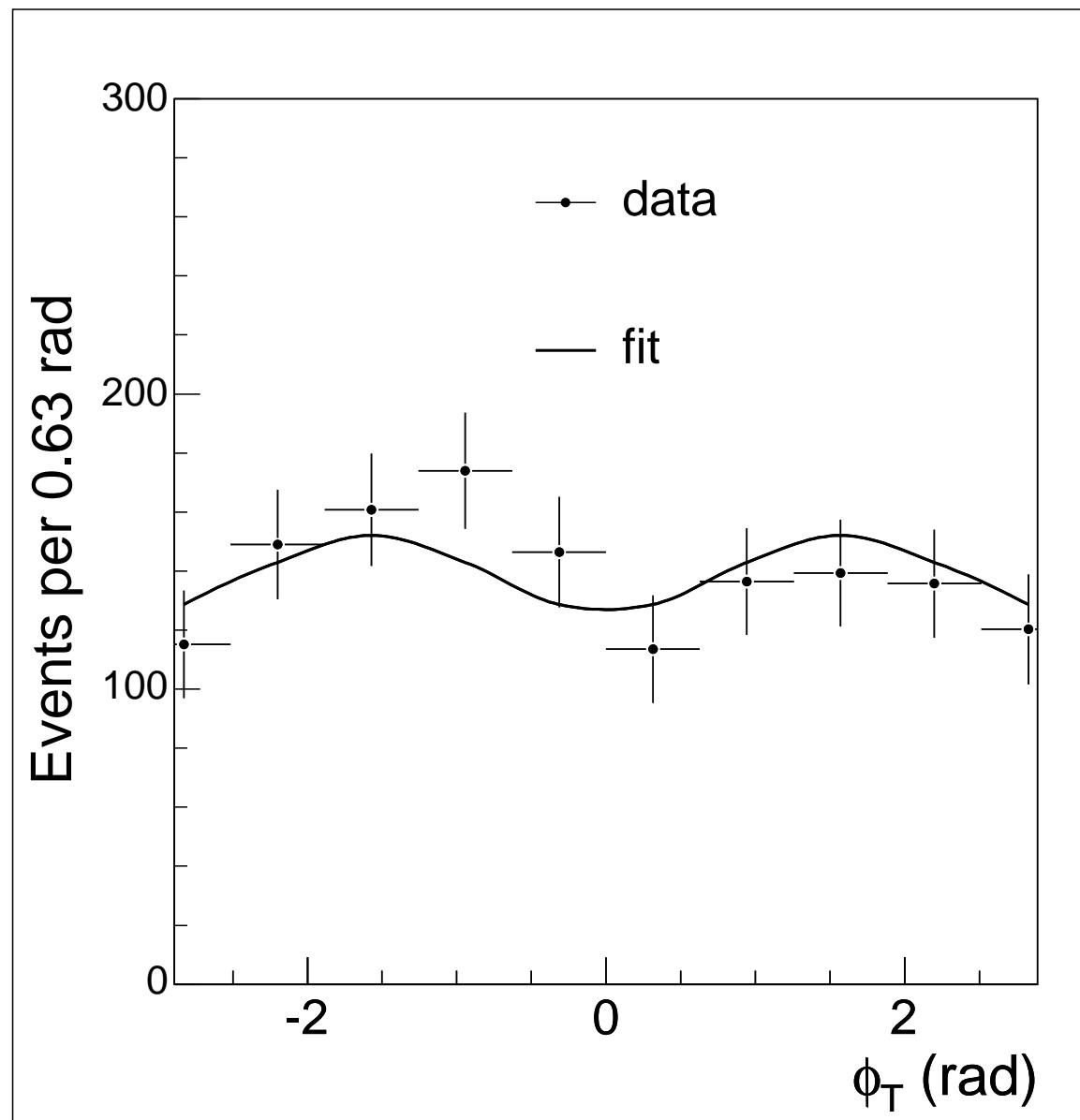
Tagged Analysis: Sideband Subtracted Angular Distrib



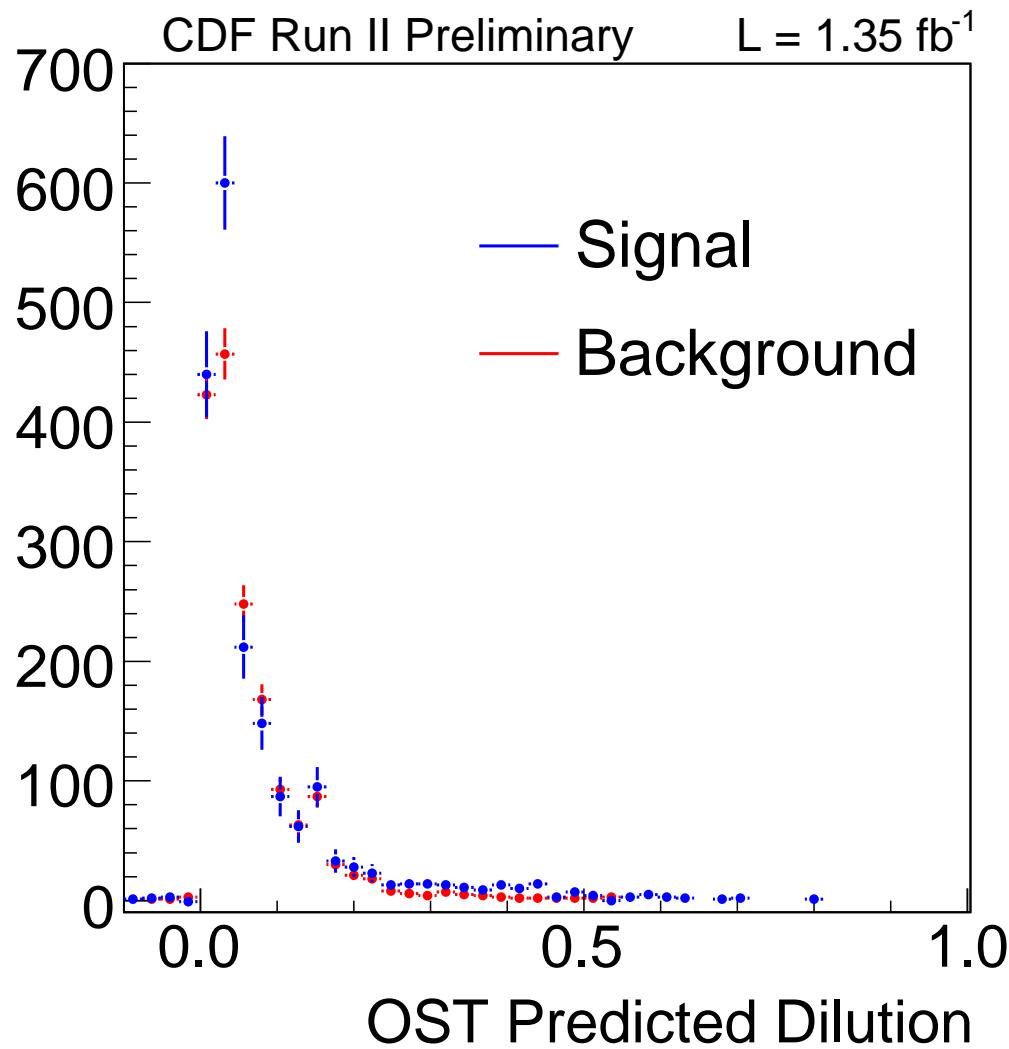
Tagged Analysis: Sideband Subtracted Angular Distrib



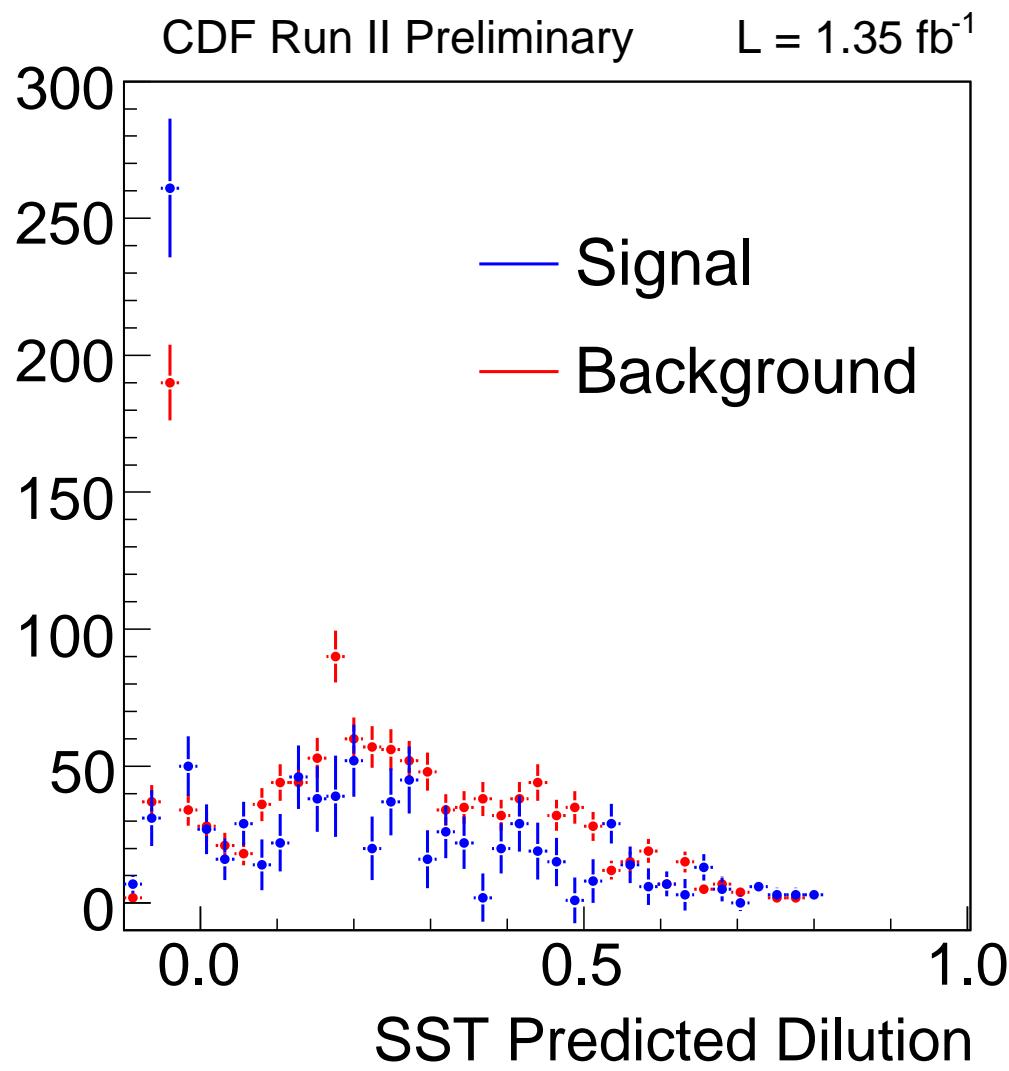
Tagged Analysis: Sideband Subtracted Angular Distrib



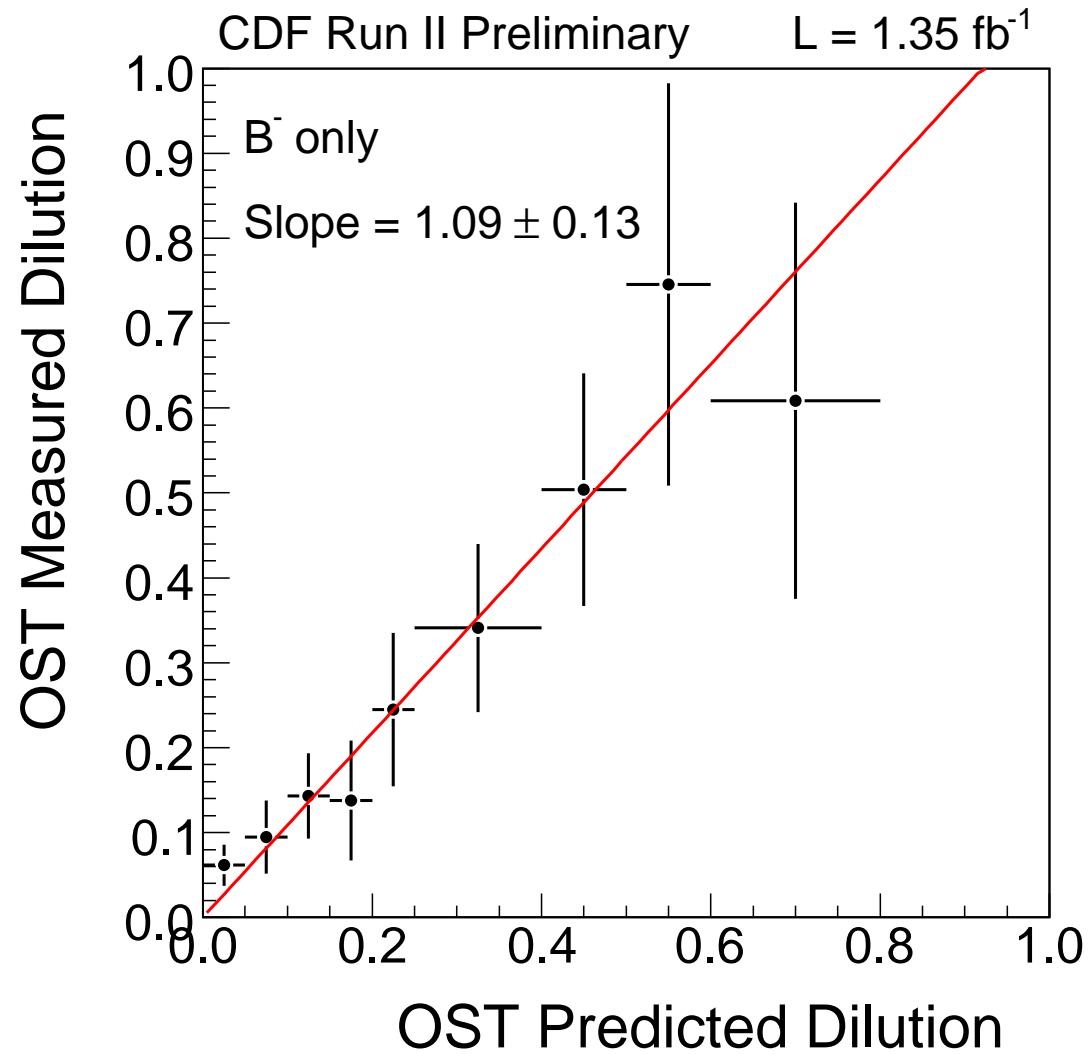
Predicted Dilution: OST



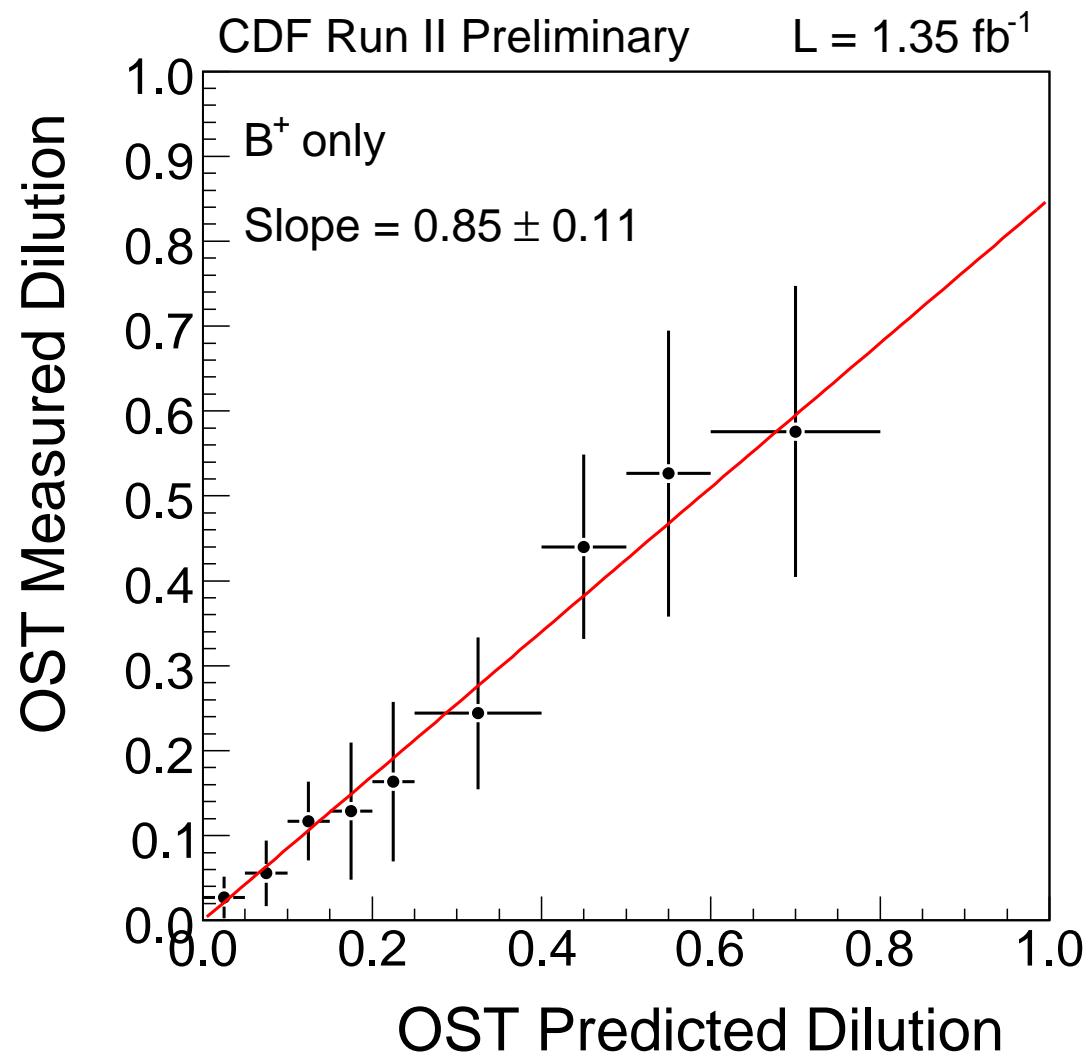
Predicted Dilution: SST



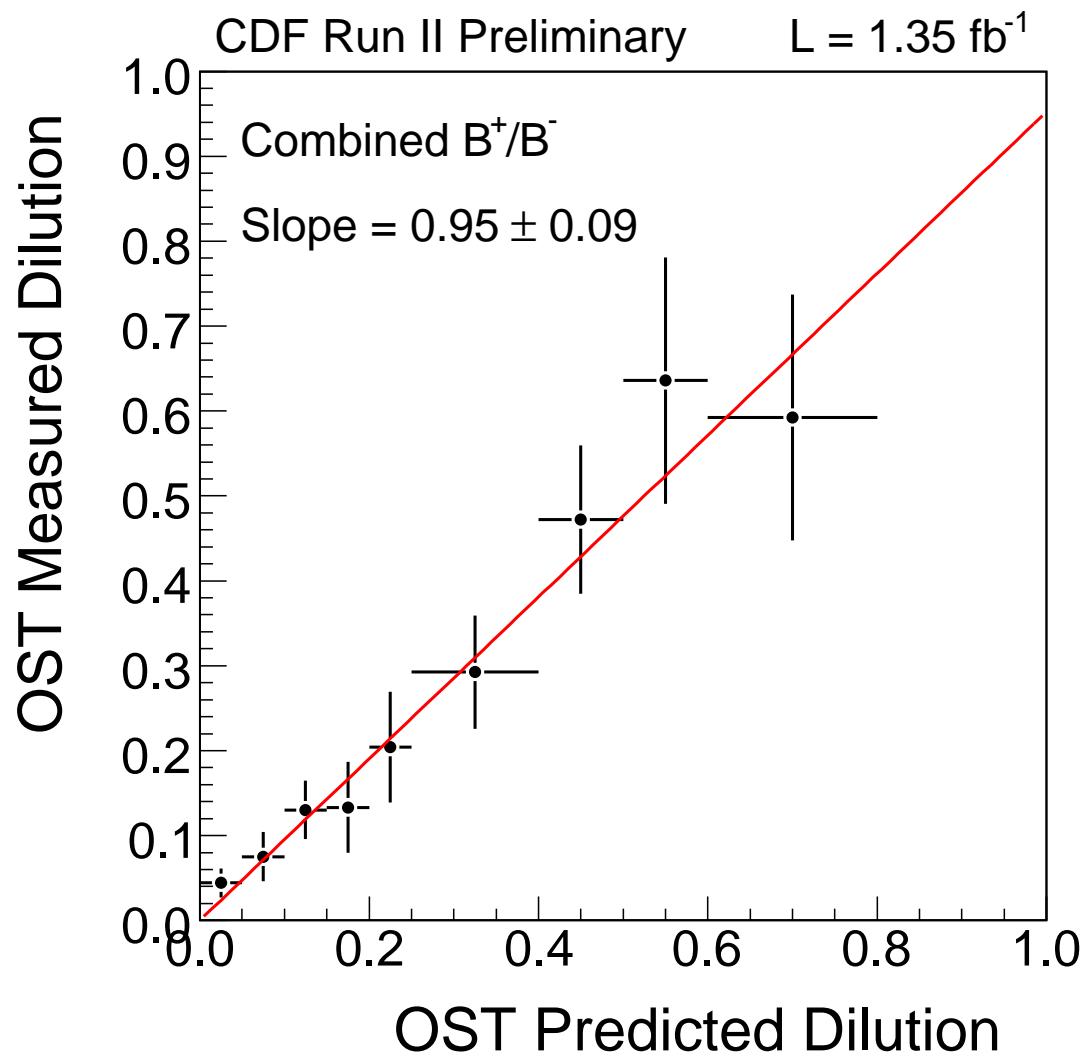
Measured vs. Predicted Dilution: B^-



Measured vs. Predicted Dilution B^+



Measured vs. Predicted Dilution $B^+ + B^-$



Likelihood Profile w/ Additional Asymmetry

